The assessment of hydrological impacts of climate change and their implications for water management across scales: from the local to European scale

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zur Erlangung des akademischen Grades
Doktor der Ingenieurwissenschaften
-Dr.-Ing.-

genehmigte Dissertation

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Tag der wissenschaftlichen Aussprache: 17. Mai 2018

Berlin 2019

Acknowledgements

This work would not have been possible without many people.

Firstly, I would like express my deepest gratitude to my supervisors at the Potsdam Institute for Climate Impact Research: Dr. Valentina Krysanova and Dr. Fred Hattermann.

Dear Valentina, I am deeply grateful for all the efforts that you have put into this work: thank you for being always available, no matter day of the week or time, providing your opinions directly and honestly, all the advices and experience that you have shared with me over these four years. Thank you for being patient with me and thanks for giving me useful insights into not only technical matters, but also into project and time management, always offering me your personal, rational and pragmatic point of view, when I lacked it.

Dear Fred, thanks a lot for all the support you have given at first during my Master Thesis, and now, during my PhD. Thanks for offering me the position and trusting that I will manage it. Thanks for always being patient, ready for helping and for all your constant support and understanding.

Second, I am deeply thankful to my supervisor at the Technische Universität Berlin: Dr. Reinhard Hinkelmann. Though we were not working on the day-to-day basis with each other, I am grateful to you for accepting me as a PhD student at your department, for being available at any point of the time and all your help in taking care of many issues, also of administrative matter. I always appreciate your support and your advices.

Third, I would like to thank my colleagues at Potsdam Institute for Climate Impact Research (in no specific order): Stefan Liersch, Hagen Koch, Iulii Didovets, Mikolaj Piniewski, Judith Stagl, Tobias Vetter, Michel Wortmann – thanks for being a great office mate also, Valentin Aich, Michael Roers, Anastassi Stefanova, Frank Wechsung who were always there to offer a professional advice, thanks for all the fruitful talks we have had and all help that you have provided to me over these years. And all our barbeques of course. Thanks for the support of Rocio Rivas, David Stevens and Matthias Büchner, who helped with model set up and data extraction during the work. I would also like to thank PIK administrative staff and, in particular, Peggy Gräfe, Gabriele Götz, Marcel Meistring, IT team and Ursula Werner for the support you have provided – nothing would have function properly without you.

Great thanks goes to all my colleagues from the "IMPRESSIONS" Project funded within the FP7 Framework of the European Commission (in no specific order): Paula Harrison, David Tabara, Tiago Capella, Joao Pedro Nunes, Marc Rounsvell, Francesco Lamperti, Simona Pedde, Jill Jäger, Katharina Hölscher, Ian Holmann, Stefan Fronzek, Catharine Fox Maule, Marianne Sloth Madsen, Linda Horwath, Laszlo Pinter and others - you are a great team of cutting edge specialists that have helped me to grow professionally and profit enormously from your experience and working style – I am really lucky to meet you all and to start my career in this project. Not to mention the dinners at the project meetings - they were unforgettable. I am thankful to Ian Holmann, who acted as an external supervisor for this Thesis – thank you for allocating your scarce time resources for that and also for coming to Berlin for my defence. Additionally, I would like to thank Andrea Roventini – for all the inspiring talks we had, from economics to arts and thanks for support and motivation that you have provided for me and this work. Thanks also again to Fred and Valentina, who offered me the opportunity to join this project, for trusting me and letting me take the responsibilities in the project during these four years – this was a vital experience for me and for my professional future.

I am grateful to the science community who provide and support the freely available data sources, without those this and many other works would never be possible.

Fourth, a very special thanks and my deepest gratitude goes to my mother, thanks for supporting me in (nearly ☺) all my plans and beginnings, I will never be who I am and where I am without you. Also this work would have been impossible without you and your constant support. Thanks also to my dad, my brother and all my family in Saint-Petersburg, which includes also my dearest friends (in no specific order): Ilona Yanaitis, Maria Bitosova, Violetta Slepova, Polina Kaminskaya, Evgeniya Akopova, Ljalja Isaeva, Roma Sysoev, Viktor Efimov, Andrey Romashow, Vadim Che, Vova Tolodov and many, many more. Though I surely have forgotten someone, but those who are meant know that I will never be where I am now without you. Thanks for your precious individualities that have shaped mine, for sharing your time with me, your understanding, support and energy.

I would also like to thank my friends here, whom I have met in Germany. Elena Matta – I have met you during strange period of my life and it was a very lucky coincidence, thanks for being in my life for all your support and understanding, for your positive energy, strength and care that you constantly take of me. You have become a very dear friend to me. And also big thanks for being a perfect flatmate! Ljubov Tupikina, you are very special, thank you for all the talks about finite infinities and random walks that we had and will have and share in the future, I appreciate it so much. Thank you for inspiring me with your passion for science. Also, in no specific order, Alvaro Sainz, Nasia Nikolau, Dasha Suomi, Soon Henry de Hassonville, lovely Sado Opera and many more - I am very lucky and happy person because of you all. Thanks to Gabriel Sauer for being close nearly until the end of this

PhD, thanks for believing in me during hard times, and, look, finally you were right and I have finished this Dissertation.

And finally, thanks to the entire lindy hop community of Berlin - I would never be able to bear all the working stress if not for the dancing evenings and nights. I have never left home from the dance classes and parties without smile on my face, even if I came in wearing the frown.

I am also grateful to Prof. Dr. Calum Brown and Ms Stephanie O'Connor for proof reading parts of this Thesis. Thank you for allocating your precious free time to it. Special thanks also to Dr. Michel Wortmann and Dr. Reinhard Hinkelmann for their efforts in correcting the "Zusammenfassung" for this Thesis.

Summary

The impacts of climate change can become a trigger for critical changes in the spatial and temporal distribution of water resources in many regions in Europe. This will lead from obviously negative effects in some regions to creation of opportunities in others. In the face of future changes: economic, social and environmental, both natural and triggered by anthropogenic activities, the effective water resources management is becoming a very intricate matter and a serious challenge for the practitioners and scientists. In order to ensure sustainability and robustness of the water management strategies, the impacts of climate change and associated risks have to be quantified and included in the water management plans.

In this Thesis an assessment of impacts of the high-end and moderate climate change scenarios on water resources in Europe was performed by means of application of the process-based eco-hydrological catchment-scale model SWIM (Soil and Water Integrated Model) coupled with the reservoir and water allocation modules. The assessment was conducted at three scales. Firstly, it was performed at the scale of Europe, considering eight representative river basins with varying climatic conditions and anthropogenic services. Then, the scale was narrowed down to a single, highly-regulated river basin in the semi-arid region in Spain, and the impacts of climate change on the reservoirs functioning were assessed. Third, a possibility to harmonize the inter-sectoral water allocation scheme within a highly altered human-hydrological system in the headwaters of the Tagus river basin, Spain in the semi-arid region under reduction in water availability triggered by the projected climate change was evaluated applying a scenario-based approach.

The extrapolation of results allows concluding that the moderate and high-end climate change scenarios of global warming across Europe would lead to decreasing trends in water availability in the southern river basins, an overall increase in discharge of the northern river basins, and increase in winter discharge and decrease in summer water flows in the central European catchments. Besides, a shift in seasonality (due to earlier snow melt) was projected in basins of central and northern Europe. The difference between the high-end and moderate global warming scenarios becomes evident after the mid-century. These findings support the previously reported results of the other studies, mostly conducted with the global-scale models, confirming the robustness of the trends found.

Further, the scaled down assessment of the water scarce catchment in southern Europe, the Tagus river basin, offers a glance on the effects of projected climate change on water resources availability and influence of potential changes on hydropower generation of the three important reservoirs in the basin. The results indicate a substantial decrease of discharge and, consequently, a strong decrease in hydropower production under both future climate scenarios. The findings also show that the vulnerability and adaptive capacity of the reservoirs depend on their size.

Further, on the example of a single water management unit in the headwaters of the same semi-arid southern catchment of the Tagus River it was shown that a shift to sustainable water management strategy and river restoration is possible even under reduced water availability in future. The results suggest that adaptation of the complex water management system to climate change and a shift to a more sustainable management of those could be parts of one joint strategy to cope with climate change impacts.

Though it is impossible to give precise quantitative assessment of all future changes triggered by climate warming, the accounting for climate change impacts may help to take right decisions in the water resources allocation and water management, to assure good environmental conditions and avoid potential socio-economic conflicts in river basins. Even in the face of significant uncertainties, associated with climate projections, managers can pursue an adaptation strategy, based on the win-win or no-regret solutions to minimize the worst potential consequences.

The work, conducted for this Thesis, has contributed to European and Iberian Case studies of the EU funded Project "IMPRESSIONS: Impacts and risks from high-end scenarios: Strategies for innovative solutions".

Zusammenfassung

Die Auswirkungen des Klimawandels können zu Änderungen in der räumlichen und zeitlichen Verteilung von Wasserressourcen in vielen Regionen Europas führen. Für einige Regionen wird es offensichtlich zu negativen Auswirkungen führen, während es in anderen auch zu Verbesserungen führen kann. Angesichts der zukünftigen wirtschaftlichen, sozialen und ökologischen Veränderungen, natur- oder menschbedingt, wird ein effektives Wasserressourcenmanagement zu einem sehr komplexen Problem und stellt eine Herausforderung für die Wissenschaft und die Praxis dar. Um die Effektivität und Robustheit von Wasserressourcenmanagementstrategien sicher zu stellen, müssen Auswirkungen und damit verbunden Risiken des Klimawandels abgeschätzt und in die Wasserressourcenplanungen mit einbezogen werden.

In dieser Dissertation werden die Auswirkungen von extremen und moderaten Klimawandelszenarien auf Wasserressourcen in Europa mittels des hydrologischen, prozessbasierten SWIM (Soil and Water Integrated Model) Models bewertet, das mit einem Wasserspeicher- und Wasserverteilungsmodul gekoppelt ist. Die Bewertung wurde auf drei Skalen durchgeführt: Als erstes wurden auf europäischer Ebene acht repräsentative Einzugsgebiete mit verschiedenen klimatischen und wirtschaftlichen Bedingungen modelliert. Auf Einzugsgebietsebene wurde der stark regulierte, semiaride Tajo Fluss simuliert und die Auswirkungen des Klimawandels auf drei Talsperren bewertet. Zuletzt wurde die Möglichkeit mittels einer Szenario-basierten Analyse bewertet, die inter-sektorale Wasserverteilung im Oberlauf des erheblich anthropogen veränderten Tajo Flusses angesichts der zukünftig reduzierten Wassermengen anzupassen.

In Anbetracht der extremen und moderaten Klimaszenarien lassen sich folgende Trends bei den Wasserressourcen Europas erkennen: Die Wasserverfügbarkeit wird sich in den südlichen Einzugsgebieten verringern und in nördlichen erhöhen. In Zentraleuropa werden sich die Abflüsse im frühen Winter erhöhen und im Sommer reduzieren. Gleichzeitig ist in Zentral- und Nordeuropa mit Veränderungen in der Abflusssaisonalität zu rechnen, die durch die erhöhten Temperaturen und damit verbundene frühere Schneeschmelzen verursacht werden. Die Unterschiede zwischen den Auswirkungen von extremen und moderaten Klimawandelszenarien werden erst ab Mitte des 21. Jahrhunderts deutlich. Die Ergebnisse bestätigen diejenigen früherer Studien, die überwiegend auf globalen Modellen basierten, und die Robustheit der gefundenen Trends.

In den südlichen Einzugsgebieten wurde die Bewertung der Auswirkungen der extremen und moderaten Klimawandelszenarien auf die Wasserressourcenverfügbarkeit und Wasserkraftnutzung bei drei repräsentativen Talsperren durchgeführt. Die Ergebnisse zeigen eine erhebliche Reduzierung der Abflüsse im Tajo-Einzugsgebiet in allen drei Talsperren unabhängig vom Klimaszenario, was zu einer starken Reduzierung der Stromerzeugung führt. Die Ergebnisse zeigen, dass die Klimavulnerabilität von Talsperren und deren Anpassungskapazität von ihrer Größe abhängig sind.

Anhand des Oberlaufs des Tajo-Einzugsgebiets wurde bestätigt, dass die Umstellung auf nachhaltige Wasserressourcenmanagementstrategien und Gewässerrenaturierung auch mit reduzierten Abflüssen möglich ist. Diese Ergebnisse zeigen, dass Anpassungsstrategien für komplexe Wassersysteme und deren Umstellung auf nachhaltigere Managementmethoden gemeinsam die Klimaauswirkungen verringern können.

Obwohl es nicht möglich ist, exakte quantitative Bewertungen von Klimaauswirkungen zu erstellen, kann die Berücksichtigung von Klimaauswirkungen helfen, richtige Entscheidungen bei der Wasserbereitstellung und dem Wassermanagement zu treffen, den ökologischen Zustand des Einzugsgebiets zu verbessern und potenzielle soziale Konflikte um Wasserressourcen zu vermeiden. Angesichts der hohen Unsicherheiten, die mit der Klimafolgenforschung verbunden sind, können Manager eine Anpassungsstrategie verfolgen, die auf „win-win“ Lösungen basiert.

Die Studien, die in dieser Dissertation beschrieben werden, haben zu den europäischen und iberischen Fallstudien des EU finanzierten Projekts „IMPRESSIONS: Impacts and Risks from high-end scenarios: strategies for innovative solutions“ beigetragen.

Publications for cumulative doctoral thesis

1. Lobanova A., Liersch S., Nunes J.P., Didovets I., Stagl J., Huang S., Koch H.,Rivas Lopez M., Maule C.F., Hattermann F., Krysanova V., 2018. Hydrological impacts of moderate and high-end climate change across European river basins. Journal of Hydrology: Regional Studies, 18, 15-30. doi: https://doi.org/10.1016/j.ejrh.2018.05.003 Preprint © 2018 Elsevier.
   The first draft of this publication forms Chapter 2 of this Dissertation

2. Lobanova A., Koch H., Liersch S., Hattermann F.F., 2016. Impacts of changing climate on the hydrology and hydropower production of the Tagus River Basin. Hydrological Processes doi: https://doi.org/10.1002/hyp.10966 Postprint © 2016 John Wiley & Son.
   The postprint version of this publication forms Chapter 3 of this Dissertation

3. Lobanova A., Liersch S., Tàbara J.D., Koch H., Hattermann F.F., Krysanova V., 2017. Harmonizing human-hydrological system under climate change: A scenario-based approach for the case of the headwaters of the Tagus River. J. Hydrol. 548, 436–447. doi: https://doi.org/10.1016/j.jhydrol.2017.03.015 Postprint © 2017 Elsevier.
   The postprint version of this publication Chapter 4 of this Dissertation

Contents

Chapter 1

1 Introduction

The vital importance of water resources for our society is doubtless. In many regions of the world water resources are adversely affected by mismanagement and anthropogenic activities like water uncontrolled withdrawals, including irrigational, urban and industrial water use, hydropower production etc. In fact, when looking at the global picture, water is rapidly becomes a scarce resource, endangering economic development, human well-being and environmental health of the rivers. Due to the fact that water bodies have natural boundaries that often do not follow the political partition of land, water shortages can also trigger political conflicts in arid and semi-arid regions, exacerbating competition for water resources, as is currently happening in Central Asian region. The strong link between humankind and the services provided by water resources and aquatic ecosystems requires a high grade of responsibility in their management, as their degradation will in turn have very strong negative effects on economic and social capital. One of the greatest technological and institutional challenges of modern water resources management strategies is the balancing and satisfaction of the competing water needs of economy, humanity and environment [1] in the face of changing future conditions.

The issue of climate change has gained wide scientific and public attention in recent decades. Climate change is a problem of global origin, but humanity will have to deal with its consequences at both global and local scales [2]. Apart from the above highlighted current issues associated with water resources usage, the hydrological cycle is extremely sensitive to even minor shifts in climate, and the consequences of the projected increase in the global temperature are very important for the water management strategies. There is a high confidence that aquatic ecosystems and many human systems, including water infrastructure, are vulnerable to the impacts of climate change and associated extreme events [2]. Climate change risks to water resources increase especially under the high-end climate change projections. On the global scale the effects of climate change will be further exacerbated by the projected increases in population and economic development, making effective management of water resources even more problematic to implement [3].

Another great challenge associated with climate change is the communication of expected impacts to stakeholders, policy makers and water managers. Current methodologies applied in order to understand the likely impacts of climate change on water resources generate significant uncertainties that are sometimes hard to grasp for practitioners. Though it is not possible to supply water managers with precise information on how climate change will impact water resources in each particular region, it is possible to supply them with a range of possible future changes and associated risks, which have to be understood and included in the water management strategy [4].

Further, the issue of providing information on climate change impacts for decision makers, water managers and stakeholders at the scales relevant for them is also of importance. Management decisions are taken at regional scales, in particular for river basins or even single water infrastructure units like reservoirs or water treatment plants, which are much finer than the resolution of climate change models [5,6]. Therefore, it is important to gain a global picture of climate impacts, which can serve as a basis for policy makers at larger scales (e.g. countries), as well as at more local scales where the water management practices are applicable [7].

1.1 Integrated Water Resources Management in Europe

Water managers have to address many different issues at the scale of river basins. These include over abstraction, river regulation, transboundary agreements, and flood and disaster management. These anthropogenic effects sometimes may have even bigger impacts on water resources than changes in climate [8]. However, in the long run climate change effects can increase and the quantification of risks to water resources associated with those are of vital importance for long-term planning, and so have to be included in regional water management strategies [4]. Management of water resources under future uncertainty is a challenging task for contemporary water managers [9]. Water resources managers have to consider future hazards and risks associated with the impacts of the climate change, and this is most possible within the Integrated Water Resources Management (IWRM) framework [4].

The concept of IWRM has been established for more than seventy years [10], and it includes the integration of natural and human dimensions in one framework, increasing the efficacy of the water management strategies. Another crucial aspect of this strategy is its iterative character, with the state of the river basin or water system being revised in cycles, which allows accounting for the changes which are constantly happening within the human and natural capital. The conventional water management strategies, which consider only past, static conditions, have shown their inefficiency in managing the water resources under internal (e.g. water management infrastructure) and external (climate change) forcing. Therefore, the IWRM is the only strategy flexible enough to cope with uncertainties of societal and natural developments, including the issue of climate change.

In Europe, the need to switch to the Integrated River Basin Management was indicated in the Water Framework Directive (WFD) that was adopted in the year 2000 as a main policy action for the protection and restoration of water bodies [11]. The ultimate goal of the iterative IWRM process as described in the WFD is to achieve “Good Ecological Status” in all river basins in Europe. It assumed that a shift to an integrated, multi-objective river basin management approach would help to restore the environmental conditions and to preserve the good ecological state of the water bodies. The state of the water bodies and IWRM strategy within the frames of the WFD has to be re-assessed in the iteration cycles.

One of the tools to achieve good environmental conditions in rivers is based on the so-called environmental flow concept, defining the minimum river flow requirements necessary to support aquatic habitats, water quality, riparian ecosystem states and morphological conditions in the river. On the other hand, the guidelines of the European Parliament on the definition and establishment of environmental flows were published only recently [12]. In the second cycle of the WFD implementation the European Commission has explicitly recognized that good ecological potential is related to both water quality and water quantity. With respect to water quantity, water withdrawals were named by the European Commission as the second biggest pressure on water resources in Europe after pollution, endangering the environmental state of many rivers. The introduction of the environmental flows is absolutely necessary to support good ecological status of rivers and must include not only the minimum water quantity in the river but also, in the case of dammed rivers, resemble the natural cycle of the flow patterns, mimicking natural high and low flow periods [13–15].

The implementation of the WFD in Europe is, obviously, only possible together with the quantification of hydrological impacts of climate change. The impacts on the hydrological state of the rivers will undoubtedly interact with the implementation of the WFD at different stages of the process, and may endanger its goals. For example, decreasing water volumes triggered by climate change may endanger the establishment of the environmental flows or the water quality in a river. Therefore, it is crucial to obtain quantitative future projections of climate change impacts on water availability over the range of scenarios of future green-house gas emissions, to grasp the entire picture of the projected global warming scenarios [4] and include them into the IWRM strategy for the river basins.

1.2 Modelling hydrological impacts of climate change to support IWRM

Modelling studies can be of great service for the investigation of impacts and testing of solutions for water management strategies. Modelling exercises are low-cost and usually rapid, which makes it possible to consider different scenarios as part of the iterative decision making process of the IWRM.

It is vital for modelling experiments to ensure reciprocal feedback between practitioners and scientists. In one way, the scientists, in order to improve the model set-up, should be supplied with some practical information for the river basins where practitioners have more experience, and conversely the modelling results have to be communicated back to the decision makers' community by the scientists [5]. The connection between the managers and scientists is crucial, as science advances very fast and changes in the knowledge base must be reflected in adjustments to management strategies [9].

The hydrological impacts of climate change are usually quantified using cascading modelling chains. At the initial step the climate change scenarios of interest are selected from the sets of the Representative Concentration Pathways (RCPs, van Vuuren [16]). Those constitute the boundary conditions for the Global Circulation Models (GCM) or Earth System Models (ESM), which simulate the atmosphere and climate at the global scale. Regional Climate Models, or RCMs, which mimic the regional aspects of climate in a given area, use the outputs of the GCMs as boundary conditions and provide projections of climate change in the region under consideration. The RCM outputs are fed into the hydrological models which provide data on the potential hydrological changes triggered by climate change. Depending on the research needs and performance of the GCM-RCM simulation results, before the introduction of the climate data into the hydrological model a bias-correction of the projections may be performed.

- Climate modelling

Global Circulation Models (GCM), or Earth System Models (ESM) simulate the entire atmosphere of the Earth, taking into account related processes, like atmospheric chemistry and aerosols effects, interactions with land surface, land ice, ocean and sea ice, carbon cycle and vegetation growth. The GCMs are driven by changes in the radiative forcing expressed in the scenarios of Representative Concentration Pathways or RCP, which were suggested by the IPCC as a replacement for the scenarios of the greenhouse gases emissions, described in the Special Report on the Emissions Scenarios [17].

The GCM models usually involve extensive computational efforts. As a result their operational grids and time steps are too coarse to account for some important faster or finer-scale regional climate phenomena. Therefore, to bridge the scale mismatch between the simulation results of climate dynamics obtained from the GCM and the regional scales, which are usually considered in the climate change impact studies, different downscaling techniques are normally applied. The downscaling of the GCMs can be performed using statistical methods such as re-sampling of observations or dynamical methods involving Regional Climate Models (RCM). Statistical downscaling has an important advantage over the RCMs, requiring much less computational resources. On the other hand, for statistical downscaling the quality and quantity of the observations in the area of interest are of a crucial importance. An additional drawback of this method is the inability of statistical methods to represent events that have not been observed before. The RCM, which are used for the short-term projections as well as for the long-term, can provide the latter information but involve much more computational resources.

Due to uncertainties associated with the climate change models, coming from imperfect model structure, and inaccuracies of the numerical methods, model parametrization and grid sizes, as well as absence of calibration, often the produced climate projections show mismatches or biases relative to the observed data in the historical period. In order to improve this and match the observed seasonal patterns and magnitude of e.g. precipitation, or number of wet days [18] after downscaling of the GCM outputs to a finer grid, a bias-correction technique is applied. There are several methods for the bias-correction of the GCM-RCM output, e.g. a simple linear scaling, quantile or distribution mapping approaches etc. [19]. For example, the linear scaling approach matches the monthly correction values, which are based on the differences between observed and simulated values of precipitation and temperature [20]. The more elaborated approach, quantile-mapping, matches the distribution function of the climatic variables obtained from climate model simulations to those obtained from the observation. At the second step this cumulative distribution function is applied to the future projection data. This method allows accounting for the spatial variation in the climate variables as well as for their interdependencies. Another method, and one of the simplest, is the delta-change approach, which is often referred to as a bias-correction technique but in fact does not correct the climate model output but rather applies the signal obtained from climate projections to the observed climate. In this Thesis climate data were bias-corrected using the quantile mapping approach.

The efficiency of the bias-correction methods application is still under discussion in the scientific community due to several drawbacks. Usually the bias-correction methods assume that the biases derived from the reference periods of climate simulation will remain stationary in the future, however the legitimacy of this statement is not assured [21]. Another two issues are the availability and quality of the observational datasets that are used for the bias-correction, and the preservation of the physical feedbacks between the climatic variables, e.g. precipitation and temperature [22].

The climate change projections applied in this Thesis consist of two different datasets, obtained from two sources: an Inter-sectoral Impact Model Intercomparison Project ISI-MIP [22,23] and the IMPRESSIONS Project [24]. The ISI-MIP dataset provides bias-corrected and bi-linearly interpolated to a finer grid GCM output, obtained from five different models, and the IMPRESSIONS dataset includes seven GCM-RCM paired simulations, obtained from the CORDEX [25,26] Database and then bias-corrected. More detailed information on the datasets can be found in Chapters 2, 3 and 4.

- Hydrological modelling

The recipients of the climate variables obtained from the GCM-RCM simulations are hydrological models. The hydrological models are simplifications of natural river basin systems, and simulate the runoff formation, evapotranspiration, biogeochemical, vegetation and transport processes. They can be used as one component of decision support systems at the river basin scale and are suitable tools to additionally support the design of water infrastructure, estimation of flood prone areas, evaluation of water management decisions and climate change impacts and their consequences. The typology of hydrological models can be organized by the following classification:

- statistical or dynamical deterministic models, depending on the underlying concept of the hydrological processes representation;
- physically-based, process-based and conceptual models, depending on the degree of physical basis and complexity of the representation of the processes at the river basin scale;
- lumped, semi-distributed or fully distributed models, depending on the degree of the spatial disaggregation of the river basins;
- global or regional-scale hydrological models, depending on the scale of model application.

The different types of models are best applicable for different purposes depending on the aim of the study, complexity of the studied phenomena, its spatial and temporal scales, etc. Global hydrological models are applied to gain understanding on how water resources will be affected globally or at the continental scale, by e.g. climate change [27,28], dam construction [29] etc. The rainfall-runoff Hydrologiska Byrans Vattenavdelning HBV [30] model can be used as an example for the conceptual hydrological model, driven mainly by topography and climate data. An example of a highly complex, physically-based, fully distributed model is the Systeme Hydrologique Europeen SHE model, developed by Abbott et al. [31]. It is probably the most well-known physically-based model, which simulates hydrological processes by solving the differential equations of the mass, momentum and energy conservation laws using the finite difference method. Though models like SHE are possibly the nearest to the reality of the physical processes at the river basin scale, they have not found wide application as they require extensive amount of input data and computational resources, making the calibration of the model a very elaborate process.

In order to assess the hydrological impacts of climate change at finer scales, e.g. river basins, the application of process-based, semi-distributed catchment-scale models have been widely accepted. Process-based hydrological models are models of intermediate complexity, which do not require an extensive data input but are sophisticated enough to represent effects of climate and land use change as well as water management infrastructure at the catchment scale. Such models are usually applied to gain understanding of how e.g. land use change, water management strategies or climate change will impact water resources in a particular river basin or subbasin.

One of the most well—known process-based hydrological model nowadays is the Soil and Water Assessment Tool SWAT model [32]. The SWAT model is an eco-hydrological, continuous, semi-distributed model which simulates hydrological, biogeochemical and vegetation growth processes at the river basin scale. Eco-hydrological models refer to type of models which combine simulation of hydrological and biogeochemical processes, in particular vegetation growth at the river basin scale. The SWAT model has become one of the most-used models and has formed an extensive modelling community in recent years due to its accessibility, technical support and continuous development. Numerous studies have been conducted all over the world with application of the SWAT model [33,34]. Recently, the SWAT model, shifting from the river basin to continental scale, has been applied across the whole of Europe [35].

Tremendous growth occurred over the last decades in hydrological modelling and in the use of modelling tools, triggered partially by the dramatic increase in the availability and accessibility of computational resources as well as by increases in the availability and transparency of different data sources needed for model set up. Many freely accessible databases offer sets of data, e.g. on topography (e.g. Shuttle Radar Mission dataset, [36]), land use (e.g. CORINE Database) or soils (e.g. Harmonised World Soil Database, Panagos et al. [37]) as well as climate observational datasets like WATCH products [38,39], as applied in this Thesis. In fact, recent information and communication (ICT) technologies, e.g. water quality and quantity sensor networks or emerging image analysis from social networks for flood or snow cover estimation [40] may offer even more possibilities to conduct more precise modelling studies.

In this Thesis, the eco-hydrological, process-based Soil and Water Integrated Model SWIM [41] was applied in order to investigate selected river basins in Europe. The SWIM model was developed, based on two models SWAT and MATSALU [42] and using as input spatial datasets (land use, soil, topography) and observational datasets of climate variables. It is also possible to include water management infrastructure like reservoirs and irrigational channels within the model.

Figure 1.1 shows the schematic representation of the SWIM model structure, with three main modules: hydrological, vegetation and biogeochemical, as well as input data. More detailed information on the model structure can be found in Chapters 2, 3 and 4.

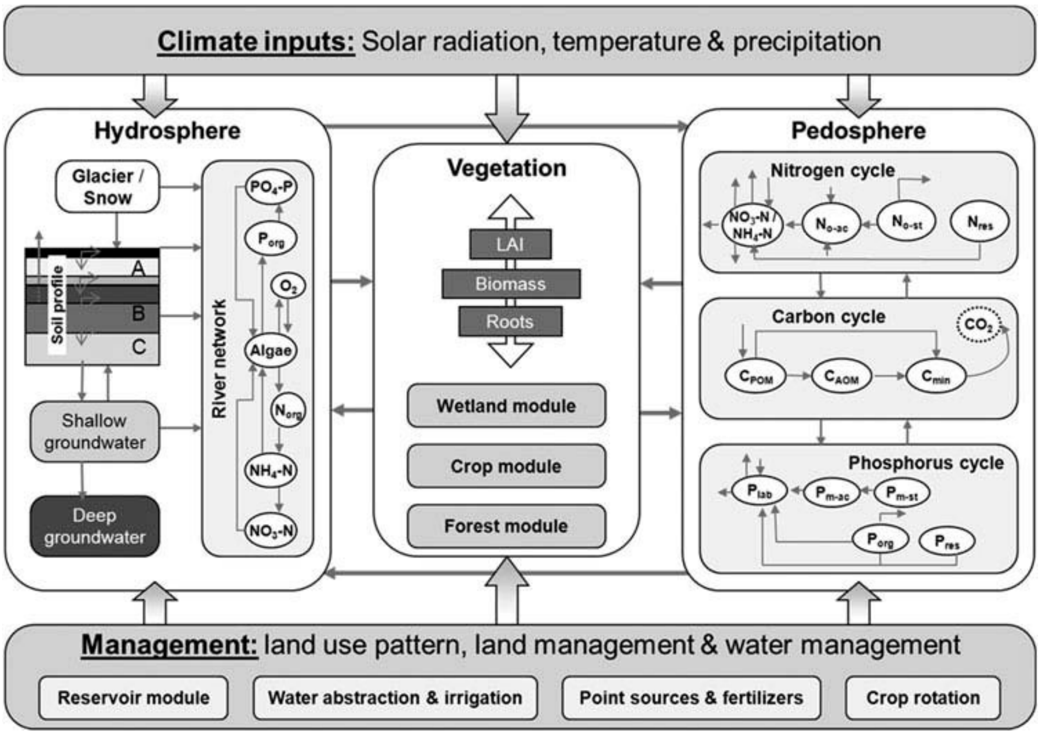

Figure 1.1 Schematic representation of the SWIM model structure applied in this Thesis [43]

- Uncertainty

Numerical models are simplified representations of the real world, and therefore contain systematic errors and uncertainties. In the hydrological impact assessment of climate change the uncertainties may arise from errors in the input data (for example observational errors), errors arising from the hydrological and climate models associated with model structure, initial conditions, parameter estimation, insufficient spatial resolution, imprecise numerical methods, or uncertainties associated with the choice and sensitivity of a given climate model to greenhouse gases emissions. The issue of uncertainty understanding and reduction has gained wide interest among the modelling community, especially for the case of the uncertainty chains, arising from the climate change modelling assessments (e.g. Hirabayashi et al. [44] Vetter et al. [45]).

In order to understand the extent of uncertainty coming from GCM-RCM coupled simulations, the so-called "ensemble" approach was proposed by the IPCC Third Assessment Report. This approach proposes to use modelling outputs from as many available GCM-RCM combinations as possible to represent the entire uncertainty spread. The agreement of trends projected by the models will indicate the robustness of the projections, assuming independence in model development. The major drawback of the "ensemble" approach is the fact that models are actually not developed completely independently from each other, and many processes are resolved in a similar way, undermining the basic assumption of the method. Further, hydrological models are also prone to erroneous results, due to absence or poor quality of the input data, parameter estimations, the need for better calibration and imperfect model structures [46]. Recently, the use of the "ensemble" approach has also started in the hydrological modelling, when in order to obtain more reliable and robust projections several hydrological models were applied (see e.g. Krysanova et al. [47], Vetter et al. [45,48], Warszawski et al. [49], Hattermann et al. [7]. Another approach to understand and reduce uncertainty is the combination of statistical and hydrological models in one framework, where the unknown input parameters are estimated using the statistical model serving as an input into the process-based model (see e.g. Montanari and Koutsoyiannis [50]).

Due to the large number of uncertainties associated with modelling chains as discussed above, one cannot supply water managers with a single precise projection in the deterministic manner, but rather with a range of plausible future projections for the river basin [4], which has to be considered in the water management strategy.

1.3 The IMPRESSIONS Project

This dissertation is based on the three research articles, which form three main Chapters. The research articles and modelling exercises produced during this work have contributed to the project "IMPRESSIONS – Impacts and Risks from High-End scenarios: strategies for innovative solutions" funded within the EU Seventh Framework. The project aims to advance the understanding of the impacts, possible adaptation strategies and probable opportunities arising under high-end scenarios of global warming.

The high-end climate change scenarios are those that correspond to an average global temperature increase of 3.2 – 5.4 ^{0}C by the end of the century, with respect to pre-industrial levels, and are exemplified by the RCP8.5 scenarios. The moderate scenarios of climate change are those represented by RCP4.5, leading to 1.7 – 3.2 ^{0}C of temperature increase by the end of the century. The high-end scenarios are becoming plausible as recent trends of greenhouse gases emissions point to the area of the high-end scenarios. The signing of the Paris Agreement in December 2015 was indeed a great achievement of a long history of negotiations, but, on the other hand, the goal of limiting the global warming to 2 ^{0}C is still very ambitious and the actions have to be taken urgently [51,52]. Therefore, it is extremely important to provide stakeholders with the picture of the impacts under both the moderate as well as the high-end scenarios.

The project provides assessment at three scales: global, European, and regional/local. The regional/local level includes three case studies: i) the Hungarian case study, focusing on two small communities in the Tolna and Veszprem counties, ii) the Scottish case study, focusing on the entire country and iii) the Iberian case study, focusing mainly on the Tagus River basin. The map with the river basins considered in each case study is presented in Figure 1.2. The schematic representation of the IMPRESSIONS project structure and concept is presented in Figure 1.3. The entire methodology of the project is based on a strong stakeholder involvement and participatory approaches [53].

The scenarios developed within the IMPRESSIONS project involve combinations of projections of the socio-economic development of the world, the so-called shared socio-economic pathways (SSPs) [54], with respective scenarios of global warming, RCPs, including the moderate (RCP4.5) and the high-end (RCP8.5) scenarios. In total, four scenarios of the socio-economic development of the world were chosen, which were derived from the global scenarios and then regionalized for Europe and local case studies, using the input from the stakeholders. These socio-economic scenarios were afterwards combined with the RCP scenarios, and were translated into input data for several models, covering different sectors, including hydrology and the SWIM model. The results obtained through the modelling have formed the basis for the second and third stakeholder workshops, during which the adaptation and mitigation strategies were proposed and discussed by the local policy makers.

Figure 1.2 Map of SWIM Model application to IMPRESSIONS case studies

The SWIM Model within the IMPRESSIONS project was applied at the European and regional scale, for three case studies: within the Hungarian case study, to the entire Danube River basin, within the Scottish Case Study to the Tay River basin and within the Iberian case study to the Tagus River basin. The results of modelling eight representative river basins in Europe provided an overview of the impacts of climatic change for the European stakeholders; and further the rivers Tay, Tagus and Danube were subject to closer investigation by the local stakeholder in the Hungarian, Scottish and Iberian case studies, respectively.

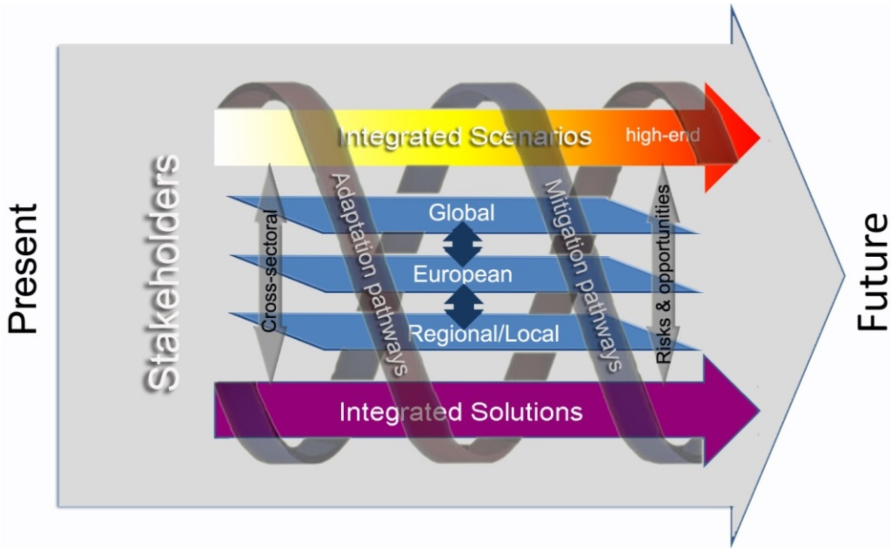

Figure 1.3 Representation of the IMPRESSIONS project concept[1]

1.4 Central research questions and the structure of the thesis

There are two central research questions investigated in this Thesis:

– How similar or different are the impacts of moderate and high-end climate change scenarios on the water resources in European river basins across different scales?

The impacts of climate change were evaluated at different scales, starting from the scale of Europe by assessing eight representative river basins in different regions to obtain the broader impacts picture, and in a second step narrowing down the assessment to the impacts on hydrological patterns and water management in the semi-arid catchment located in Southern Europe.

The second question concentrates on the implications of water management strategies under climate change in a highly regulated human-hydrological system:

– Is it possible to implement sustainable operation of water infrastructure in the face of reduced water availability under climate change, and what effect would that have on the performance of the infrastructure under consideration?

[1] *source: http://www.impressions-project.eu, copyright: IMPRESSIONS Projec/Dr. Paula Harrison*

The three research articles form the main body of the Thesis – Chapters **2**, **3** and **4**.

Chapter 2 provides an overview of hydrological impacts of moderate and high-end climate change across Europe, taking eight representative river basins covering different climatic zones as case studies. The results of this paper contributed to the European Case Study of the IMPRESSIONS project and aims to gain a broader context of the impacts of moderate and high-end climate change on the water resources in Europe. While continental or global studies on climate change impact assessments are popular, with many recent investigations, [28,44,55], these often employ global scale models, whose performance can be constrained by coarse resolution and the absence or limited nature of calibration [7]. This Chapter was intended to provide a general picture of how climate might impact the rivers by application of a more sophisticated process-based model including the water infrastructure for selected basins in the different hydro climatic zones. Additionally, the aim was the verification of trends found by previous studies, conducted with global models. This study can serve as a support for decision makers at larger scales, for example politicians. The paper was submitted to the Journal of Hydrology: Regional Studies, in 2017.

Chapter 3 narrow down the scale of the impact study and focuses on the impact of the climate change scenarios on the discharge of the Tagus River specifically and on the performance of water infrastructure, in particular the three representative reservoirs with installed hydropower plants at three different locations in the basin. For this assessment different climate change projections were used. The scenarios were obtained from the ISI-MIP project, as the IMPRESSIONS scenarios were under development at that time. The Tagus River is an important source of water for irrigational uses within the basin itself and for the south of Spain, supplying water for the so-called "greenhouses of Europe" – agricultural areas in the South of Spain where a massive amount of vegetables and fruits are grown to supply the European market. The Tagus River basin is also one of the most highly regulated rivers in Europe, and the importance of installed infrastructure cannot be undermined, as it provides water resources for agriculture, hydropower production and water supply for many cities, including Madrid and Lisbon. While there were several studies on the assessment of impacts of climatic change on the water resources of the Tagus River performed recently [56,57], our study was the first to include the infrastructure in the river basin, which is of ultimate importance for the river, within one modelling framework. Three reservoirs representative for the catchment were selected for the assessment: two large storages, located in the mountainous areas, and one small one at the main river, of the run-of-the-river type. Additionally, our study provides modelling results that support the statement that depending on the size of the reservoir and its location, the impacts and adaptive capacity of the reservoirs are different. This paper was published in the Hydrological Processes Journal in 2016.

Chapter 4 narrows down the spatial scale of the impact assessment further, and focuses on the water infrastructure unit in the headwaters of the Tagus River basin. The Tagus headwaters represent a highly modified human–hydrological system, where people have substantially altered river flows through water management infrastructure. The concept of this paper has emerged after the first stakeholder workshop, where local stakeholders expressed concerns regarding the environmental state of the river in the headwaters. The current management strategy has aggravated the environmental state of the river through the unbalanced allocation of water resources between the economy and environment, which was even portrayed in the media as “La Guerra del Agua”, or “war on water”. The conventional water management approach applied in this region does not account for the provision of environmental flows and gives all the preferences to the satisfaction of the economic needs for water. Apart from violating the requirements imposed by the WFD, obviously, such a situation will lead to even more drastic consequences in the face of projected dramatic water decreases due to climate change. In this Chapter three different management strategies were introduced and assessed in order to compare their performances under the projected climate change. They comprise a) current management strategy, b) the strategy proposed by the Spanish Ministry of Agriculture, and c) an environmentally-oriented strategy that considers the implementation of environmental flows that can potentially reduce the negative effects of a climate change. For this study a methodology consisting of a process-based model of intermediate complexity (SWIM), coupled with a conceptual reservoir and water allocation module, was developed to create an integrated assessment modelling framework. Within this modelling framework it was possible to calibrate the entire system and represent the dynamics of this human-hydrological system successfully. Such an approach can be used in other systems, similar to the Tagus headwaters, for long-term planning and management. An important result for this study (for this region but also for others with similar problems) is that while the stakeholders will have to deal with reduced water availability in any scenario considered, it is still possible to implement a shift to a more sustainable water allocation considering both economic and environmental aspects. Such a strategy may also increase the resilience of the system to projected changes in climate, as indicated by the results of this study. This article was published in the Journal of Hydrology in 2017.

The two latter papers reflect the work conducted for the Iberian regional case study of the IMPRESSIONS project. The research questions were based on the needs and concerns of the local stakeholders, which were expressed at the first stakeholder workshop. As the framework of the IMPRESSIONS project allowed the involvement of the stakeholders at the early stages of the project, it made it possible to address their needs in the modelling framework.

Chapter 5 summarizes the results of **Chapters 2 - 4** with respect to the central research questions and implications for water managers and provides an overview of limitations of applied methodology, as well as suggestions for the future research.

Chapter 2

2 Intercomparison of hydrological impacts of moderate and high-end climate change across European river basins

This chapter is a draft version of the article:

Lobanova, A.; Liersch, S.; Nunes, J. P.; Didovets, I.; Stagl, J.; Huang, S.; Koch, H.; Rivas López, M. del R.; Maule, C. F.; Hattermann, F.; Krysanova, V. Hydrological impacts of moderate and high-end climate change across European river basins. *J. Hydrol. Reg. Stud.* **2018**, *18*, 15–30 doi: https://doi.org/10.1016/j.ejrh.2018.05.003

2.1 Abstract

The projected changes in climate may impact hydrological patterns of river flows and water resources availability across Europe in different ways: from obviously negative effects in some regions to creation of new opportunities in others. To provide a glance onto hydrological impacts of the moderate and high-end climate change scenarios of global warming across Europe, this climate impact study focuses on the eight Europe an representative basins: Tagus in Iberian Peninsula; Emån and Lule in Scandinavia; Rhine, Danube and Teteriv in Central and Eastern Europe; Tay on the island of Great Britain and Northern Dvina in North-Eastern Europe. The eight river basins are characterized by varying degrees of anthropogenic influences: from almost pristine conditions (Northern Dvina) to highly regulated rivers (Lule, Tagus), and were selected in four different major climate zones to cover a range of climatic conditions across Europe. To assess the projected changes, the process-based eco-hydrological model SWIM (Soil and Water Integrated Model) was set up, calibrated and validated for the basins. The SWIM was driven by the bias-corrected climate projections obtained from the Global Circulation Model and Regional Climate Model coupled simulations under the RCP4.5 and RCP8.5 global warming scenarios. The

results show robust decreasing trends in water availability in the southern river basin Tagus, an overall increase in discharge of the most northern river basin Lule, increase in the winter discharge in northern and central European catchments and shift in seasonality in Northern Dvina and Lule. This analysis was embedded within the European Case Study framework of the EU funded project "IMPRESSIONS: Impacts and risks from high-end scenarios: Strategies for innovative solutions".

2.2 Introduction

Climate change is one of the world's most important global challenges, which will have global as well as regional consequences, and is expected to affect all aspects of modern humanity [2]. The Paris Agreement entered in force at the 21st Conference of Parties (COP21) in 2015 indicated a great success of more than 20 years of negotiations, but also imposed a significant challenge to the contemporary society by setting the goal of limiting the global warming to 2^0C, while aspiring to 1.5^0C [58,59]. This goal is ambitious as now the trajectories of the greenhouse gases emissions are pointing to the high-end climate change scenarios above the agreed threshold, and this development still remains probable, if global actions are not taken urgently.

The flow regimes of rivers are being modified all over the world by anthropogenic impacts, such as water management operations and land use changes. Some measures put freshwater resources at significant stress, and climate change is expected to alter the hydrological conditions further, posing additional pressure on water resources and aquatic ecosystems. The climate change risks have to be understood, quantified and incorporated into water management strategies at the regional level [4]. All adaptation measures, including those of "no-regret" type have to be based on a solid understanding of the current situation and possible future trends [60], both long-term and short-term. Hydrological modelling is a primary tool to obtain projections on how climate change would impact water resources and hydrological patterns of river basins.

In general, there is a voluminous amount of literature on the impact of climate change on hydrological cycle and water resources covering different scales: from river basins to continental and global scales. Most of the continental and global scale studies employ the global scale hydrological models, as the application of a regional model to all river basins in a continent, e.g. in Europe, would result in significant calibration efforts and higher input data requirements.

At the scale of Europe, Papadimitriou et al. [55] conducted a study on impacts of the high-end climate change on river discharge in eight selected European river basins applying the non-calibrated global hydrological model JULES [61]. They have found an increase in the number of days with low flow for Central and Southern Europe (Rhine, Danube, Guadiana), and an increase in low flows for Scandinavia (Kemijoki river). Further, several studies, conducted with different global models (e.g. WaterGAP, Mac-PDM.09), have projected an increase of discharge in the high-latitudes and decrease in the Mediterranean and Southern Europe [62–64], and seasonal changes in the snowmelt driven rivers, where discharge in winter is increasing, while the summer discharge is decreasing [65,66].

Due to uncertainties associated with global hydrological modelling, which are usually higher compared with those related to regional hydrological models [7,62,67], coarser resolution of the input data and models themselves, difficulties with calibration of the global models, as well as inability of most of the global models to take into account water management infrastructure [35], it is suggested to verify trends by application of the basin-scale models.

Further, there are some continental-scale studies performed with the pan-European models, which are partly calibrated. Donnelly et al. [68] applied a multi-basin model E-HYPE to the entire Europe, which showed good simulation results, and can be used for climate impact studies after some improvements, regarding input data and additional calibration. Roudier et al. [69], applying three pan-European models, LISFLOOD [70], E-HYPE [68] and VIC [71], found that drought events may increase in Southern Europe, in particular, in Southern France and Spain, and the frequency of flood events may increase in Northern Europe, if the global temperature will increase by +2 ^{0}C. A study of Alfieri et al. [72] applied the distributed hydrological model LISFLOOD driven by the high-end climate change scenario in major river basins across the entire European region. They found decrease of the runoff in the Southern Europe and increase of the runoff in Northern, and no specific trends for the discharges in the Central Europe. However, the abovementioned analyses were focused on the extreme events frequency analysis or on the validation of the pan-European models, and not on the general picture of the hydrological impacts of projected climate change.

Regarding the hydrological impact assessments performed with the regional scale hydrological models, it usually focuses on individual regions, often single river basins, and studies encompassing large areas are rare [45,73]. Recently, a Special Issue in Climatic Change (see editorial Krysanova and Hattermann [74]) addressed the issue of intercomparison of regional-scale hydrological models and climate change impacts across twelve large river basins around the globe (including two basins in Europe: Rhine and Tagus), fulfilled by the efforts of the ISI-MIP project [23] group.

This study aims to close the existing gap and provides an assessment of trends in the long-term mean annual dynamics of river discharge in eight representative European basins triggered by climatic change. For that, an eco-hydrological process-based catchment scale hydrological model was applied, which was calibrated and validated for each case study in advance and accounted for water management operations, where applicable. It used a more elaborated approach, when compared to the previous European-scale studies. An assessment and intercomparison of the moderate and high-end climate change impacts on river discharge across different regions in Europe, focused on eight river basins was provided: Tagus in Iberian Peninsula; Emån and Lule in Scandinavia, Rhine in Central Europe, Danube and Teteriv in Central and Eastern Europe, Tay on the island of Great Britain, and Northern Dvina in North-Eastern Europe. These basins were selected within the European Case Study of the EU funded project "IMPRESSIONS: Impacts and Risks from the high-end scenarios: strategies for innovative solutions".

This assessment considers two future climate change scenarios of moderate (RCP4.5) and high-end (RCP8.5) global warming, and two future time slices: intermediate (2041-2070) and far future (2071-2100), evaluated with respect to the reference period (1981-2010). Current study complements the picture of the European scale assessments done before, and verifies the trends found in the previous studies fulfilled with the global scale models.

2.3 Case study basins

The basin drainage areas are ranging from 4500 km^2 (Emån) to 817000 km^2 (Danube). The basins are characterized by different climate conditions (see Figure A1 of Appendix I that provides an overview on climatic zones after Koppen Geiger for the basins). They have different seasonality of flows, different soil and hydrological characteristics as well as different anthropogenic activities, including irrigation, hydropower production, navigation, water supply and fishing. The most important characteristics of the eight river basins under consideration are summarized in Table 2.1 and in part A2 of Appendix I and the location of river basins is shown in Figure 2.1.

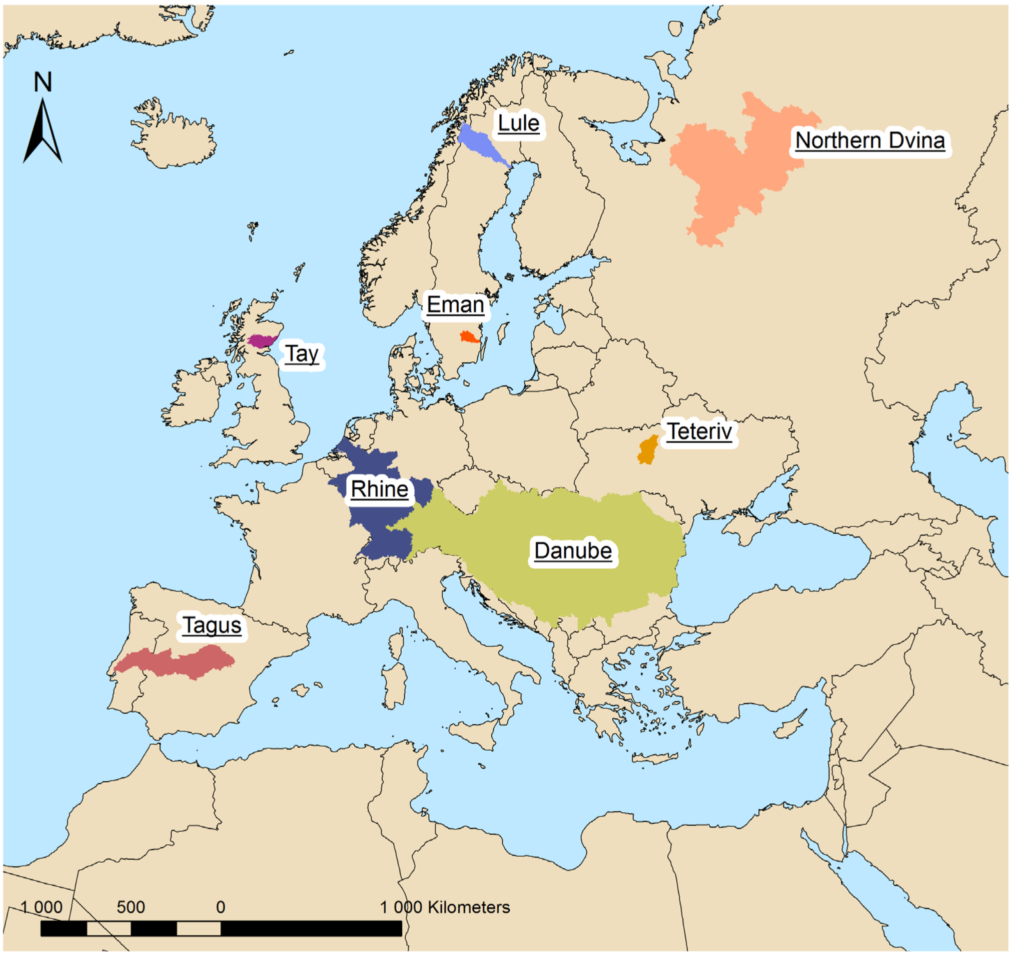

Figure 2.1 Coverage of the European Case Study: eight river basins under consideration

Table 2.1 Major characteristics of the case study river basins

Name	**Location**	**Catchment area, km²**	**Length, km**	**Mean Q, m³/s**	**Anthropogenic functions**	**Anthropogenic alterations considered in SWIM or not**
Tagus	Iberian Peninsula	80000	1000 (approx.)	500	Hydropower production, irrigation, public water supply	Yes, 16 largest reservoirs and the Tagus-Segura water transfer are included
Tay	Island of Great Britain	5200	188	170	Hydropower production, industrial and public water supply	No
Lule	Scandinavia	25000	350	500	Mainly hydropower production	Yes, 5 major reservoirs
Emån	Scandinavia	4500	220	30	No	No
Northern Dvina	North-Eastern Europe	350000	744	3500	Navigation	No
Rhine	Central Europe	185000	232	2500	Navigation, irrigation, water supply	No
Danube	Central and Eastern Europe	817000	2860	7000	Irrigation, hydropower production, navigation	No
Teteriv	Eastern Europe	15100	2860	33.8	Irrigation, pond-fishing, industrial water supply	No

2.4 **Methods**

2.4.1 SWIM Model

The Soil and Water Integrated Model (SWIM) is a process-based deterministic eco-hydrological model, based on two earlier created models: SWAT [32] and MATSALU [42]. The model is described in Krysanova et al.[41]. The SWIM model can be seen as an assemblage of numerical representations of physical processes of hydrological cycle and related processes (vegetation growth, nutrient cycling and erosion) at the river basin scale. These physical processes are mathematically interpreted with similar levels of complexity, and form four main modules of the model: hydrological processes, groundwater, biogeochemical cycles and plant growth. SWIM operates on a daily time step and uses climatic, land use, topographic, vegetation and soil datasets as input files.

The topographical map of a catchment serves as a basis to create a subbasin map, which is later intersected with land use and soil maps to identify the so-called HRUs – Hydrological Response Units or hydrotopes – areas within each subbasin, where a unique combination of land use and soil type is present. The identical HRUs, the ones which have the same land use and soil types in a subbasin, are assumed to have the same hydrological "behaviour", and are later combined into hydrotope classes within each subbasin, and modelled as one subarea. The components of hydrological cycle, nutrient cycling and sediment loads are calculated at the hydrotope level and added together for subbasins. After that the lateral flows of water, nutrients and sediments are routed through the basin, using conceptual representation of the open channel hydraulics – the Muskingum method, taking into account transmission losses.

More than 20 years of application history of the SWIM include development of model versions for specific processes (wetlands, nutrients in streams, reservoirs, etc.) and many stories of successful application as well as some failure cases, as thoroughly discussed in Krysanova et al. [43]. The SWIM model has been successfully applied for investigation of different hydrological phenomena, like impacts of climatic change on stream flow [75–78], on agricultural production [79], and on extreme hydrological events [75,80–82], as well as for analysis of the glacier lakes outburst floods [83] and hydrological impacts of irrigation activities [84].

2.4.2 Reservoir module

The reservoirs module of SWIM is a conceptual representation of the storage/release processes at dams and reservoirs [85]. It is fully integrated in the SWIM model and can represent three management strategies, depending on the minimum discharge from reservoirs (e.g. for environmental needs), minimum and maximum reservoir volumes in a given month, or firm hydropower production target. The reservoir module requires a volume-discharge-surface area relationship for each reservoir, and also the inflow, outflow and stored volume time series for calibration and validation of the management process. The reservoir module can also simulate the hydropower production, and requires data of the hydropower plant installed as an input for the calculation of the daily produced hydropower.

Each reservoir in the catchment is integrated into the subbasin map of the river basin under consideration as a separate subbasin. The precipitation over the reservoirs as well as evaporation rates and seepage of water to the groundwater are considered.

2.4.3 Water allocation module

The water allocation module (WAM) and its application for the simulation of the Tagus-Segura Water Transfer were described in detail in the work of Lobanova et al. [86]. The WAM simulates water withdrawals by, e.g., irrigation channels and inter- and intrabasin transfers of water, for example for drinking water supply. The module operates on a daily time step, and enables water withdrawal from one subbasin and assignment to the other subbasin within the river basin, or simply outside the basin on the next day, taking into account transmission losses, e.g. due to evaporation. In the case of the Tagus-Segura water transfer, the observed withdrawn values over the calibration and validation periods were applied within WAM, and for the future projections the mean values over the entire observed period were applied, as the projection of the withdrawal evolution was beyond the scope of this study. The analysis of the possible water allocation scenarios in this area under the projected climate change scenarios can be found in Lobanova et al. [86].

2.4.4 Input data

The input data needed to set up the SWIM model for a river basin are land use map, soil map, digital elevation model (DEM) and climate data, as well as observed runoff for calibration and validation of the model.

The CORINE land use database and the DEM from the CGIAR database [36], both with the resolution of 100 m, were used for seven case study basins except the Northern Dvina. In the case of the Northern Dvina River the input datasets were different. In particular, the land use data was obtained from the global CORINE dataset with a coarser resolution of 250 m, which is covering the European part of Russia. The DEM model used for this catchment was from the ASTER dataset, with the resolution of 30 m, which provides DEM covering the entire globe [87]. The ASTER dataset was the only one DEM available for the Northern Dvina River, as the CGIAR dataset covers the globe only until 60^{th} latitude. The soil data for all basins was extracted from the European Soil Data Centre [37].

To calibrate and validate the SWIM model, the gridded climate WATCH Era Interim Forcing Data [39] were used. The WATCH Era Interim covers the entire globe and provides synthetically generated climatic variables, corrected to observations. The WATCH ERA Interim dataset is provided on a grid with a resolution of 0.5 ^{0}C and covers time period 1979 - 2010. The observed discharge data at the outlets of the basins were obtained from the Global Runoff data Centre (Koblenz, Germany) GRDC database for all basins except for the Tagus River basin, for which the observed data at the Almourol gauge were provided by the SNIRH database of the Portuguese Ministry of Environment.

Initially, the Rhine River model was set up and described in Huang et al. [88], the Danube River Model in Stagl and Hattermann [77], and the Teteriv River model in Didovets et al. [89]. The first two models were initially calibrated to WATCH Era 40 [38], and for their application for the European Case study in IMPRESSIONS the models were re-calibrated to WATCH Era Interim.

2.4.5 Calibration and validation

Two main criteria of fit between the observed and simulated discharges were used: the Relative Volume Error, RVE, and the Nash-Sutcliffe Efficiency, NSE. The RVE is a total deviation in the volume of water discharged, expressed in percent, and the NSE is an efficiency coefficient, which relates a sum of squared differences between the observed and simulated discharges to the variance of the observed values of discharge. The RVE coefficient can vary from -100 to +inf, where 0 indicates a perfect fit, and the NSE coefficient from –inf to 1.0, where 1 indicates a perfect fit. The specific limits for both criteria, which correspond to a "good" performance of model can be found in Moriasi et al. [90].

The SWIM model was calibrated and validated against the observed discharge data series on the daily time step for all eight basins. The calibration and validation periods were different for each river basin, subject to discharge data availability. Due to the fact that two river basins were regulated, it was practically impossible to represent properly the daily dynamics of river flow there. Therefore, it was decided to calculate the criteria of fit on the monthly time step in all cases.

2.4.6 Climate scenarios

The climate change projections used in this study were developed within the IMPRESSIONS project. The projections were obtained from the CORDEX coupled GCM (Global Circulation Models) – RCM (Regional climate Models) simulations. The downscaled data was bias-corrected to the "observed" data WATCH Era Interim using the quantile mapping method [19,91].

The projections include seven GCM-RCM coupled simulations, forced by RCP4.5 and RCP8.5 scenarios of increase in the radiative forcing. The projections were selected to cover the full range of future climate projections from 1.1 °C to 4.2 °C [24].

The Northern Dvina River basin lies exactly at the border of the EURO-CORDEX domain, and therefore the RCM simulation results may not represent this area with sufficient accuracy due to the strong influence of boundary conditions inherited from the GCMs. Therefore, it was decided to use the raw GCM output for this basins, and then to bias-correct it applying the same quantile mapping method as for the other basins.

2.5 **Results and discussion**

2.5.1 Calibration and validation

In general, the performance of the SWIM model during the calibration and validation periods for all selected basins was satisfactory. Figure 2.2 depicts the long-term average seasonal dynamics observed and simulated with SWIM driven by the WATCH Era Interim data at the outlets of the selected basins over the respective calibration and validation periods together. Table 2.2 summarizes the NSE and RVE values obtained for the calibration and validation periods with the monthly time step for each case study basin.

The SWIM model performed satisfactory in all case studies, showing very good to acceptable performance, based on ranges specified in Moriasi et al. [90]. In terms of NSE values the best model fitting was found for the Northern Dvina basin, and the worst for the Rhine and Lule basins. The largest RVE was obtained for the Tagus River. This can be explained by the continuous development of irrigation channels and increase in water consumption for irrigation during the calibration and validation periods in the Tagus, which were not taken into account in the model, as discussed in Lobanova et al. [76].

When looking at the seasonal dynamics, one can observe that the SWIM model simulations reproduce observed dynamics well in most cases, but also exhibit some deviations in certain sub-periods in some cases. In the case of the Tay River, the timing of flow was not properly met, probably, due to absence of the regulated lakes integration into the model set up.

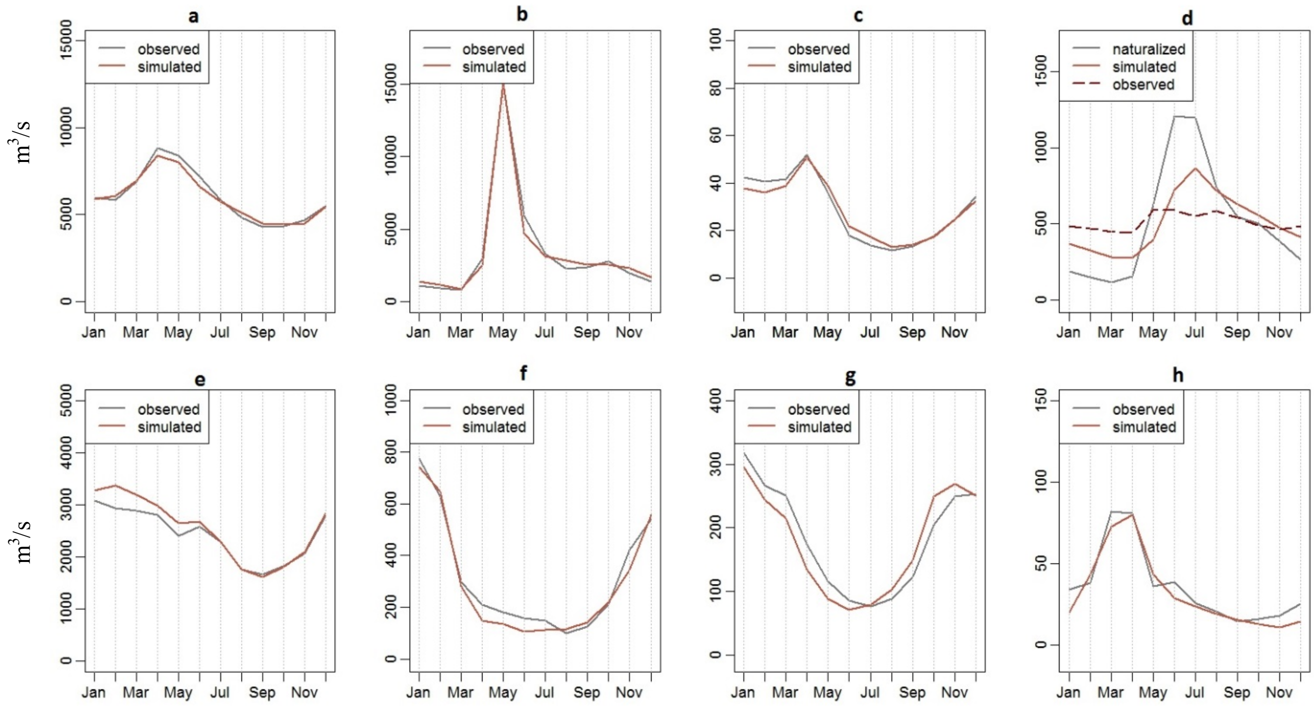

Figure 2.2 The long-term mean annual dynamics, observed and simulated with the SWIM model, driven by the WATCH Era Interim dataset for the eight case study basins: a) Danube; b) Northern Dvina; c) Emån; d) Lule; e) Rhine; f) Tagus; h) Tay; and i) Teteriv

In the case of the Tagus River, the low flows during summer were underestimated, possibly due to similar reasons, as this river is one of the most highly regulated in Europe, there are more than 40 large reservoirs in the catchment, whereas in the SWIM model only 16 major reservoirs were included. Still, the inclusion of reservoirs has increased the performance of SWIM in this case significantly, as discussed in Lobanova et al. [76], but some uncertainty due to water management infrastructure, which was not taken into account, is left.

Table 2.2 The Nash-Sutcliffe Efficiency and Relative Volume Error values for the calibration and validation periods for the case study basins with the monthly time step

River		**Nash-Sutcliffe Efficiency**	**Relative Volume Error, %**
Danube	Calibration (1990-1999)	0.86	-4.6
	Validation (2000 - 2008)	0.87	-5.9
Northern Dvina	Calibration (1990 - 1999)	0.93	-3.2
	Validation (2000 - 2009)	0.95	-8.0
Emån	Calibration (1991-1995)	0.86	8.6
	Validation (1996-2001)	0.78	-9.5
Lule (naturalized flow)	Calibration (1999-2005)	0.69	-0.9
	Validation (2005-2011)	0.62	-0.3
Rhine	Calibration (1981-1991)	0.69	-0.1
	Validation (1992-1999)	0.52	-0.1
Tagus	Calibration (1987-1993)	0.82	15.0
	Validation (1994-1999)	0.81	-12.0
Tay	Calibration (1980-1992)	0.85	1.6
	Validation (1992-2001)	0.88	1.0
Teteriv	Calibration (1999-2004)	0.82	-10.5
	Validation (2004-2009)	0.57	10.0

However, the most explicit example of the effects of anthropogenic activities on river flow in this study is the Lule River basin. In Figure 1d one can see discharge measured at the outlet of the river, the naturalized flow of the river simulated with the HYPE model [92], and discharge simulated with the SWIM model considering four major reservoirs. One can observe that the natural dynamics of the river was completely transformed, eliminating the flow variability, making flow nearly constant throughout the year. By introducing the reservoirs in the SWIM model the dynamics could be brought closer to the observed one, however still it is far from the perfect fit. The inclusion of more reservoirs could improve the performance of the model further.

2.5.2 Representation of the historical discharge dynamics by SWIM driven by climate models

To check the performance of the bias-corrected climate data in the historical period, the observed discharge was additionally compared with discharge simulated by SWIM driven by the selected GCM-RCM projections (Figure 2.3). The systematic overestimation of flows with SWIM driven by the GCM-RCM climate runs was found in two cases: for the Rhine and Danube River basins. In all other cases the simulated dynamics was similar to that driven by the Era Interim data. The long-term mean annual discharge dynamics in the Teteriv River basin was represented satisfactory, even though the catchment is situated in the same region as the Danube. In the cases of the Emån and Tagus there is some uncertainty in representing winter flows, what is indicated by a larger spread of model outputs. As for the Tay, the lag in timing of the high and low flows follows the pattern of the SWIM simulation driven by the Era Interim data.

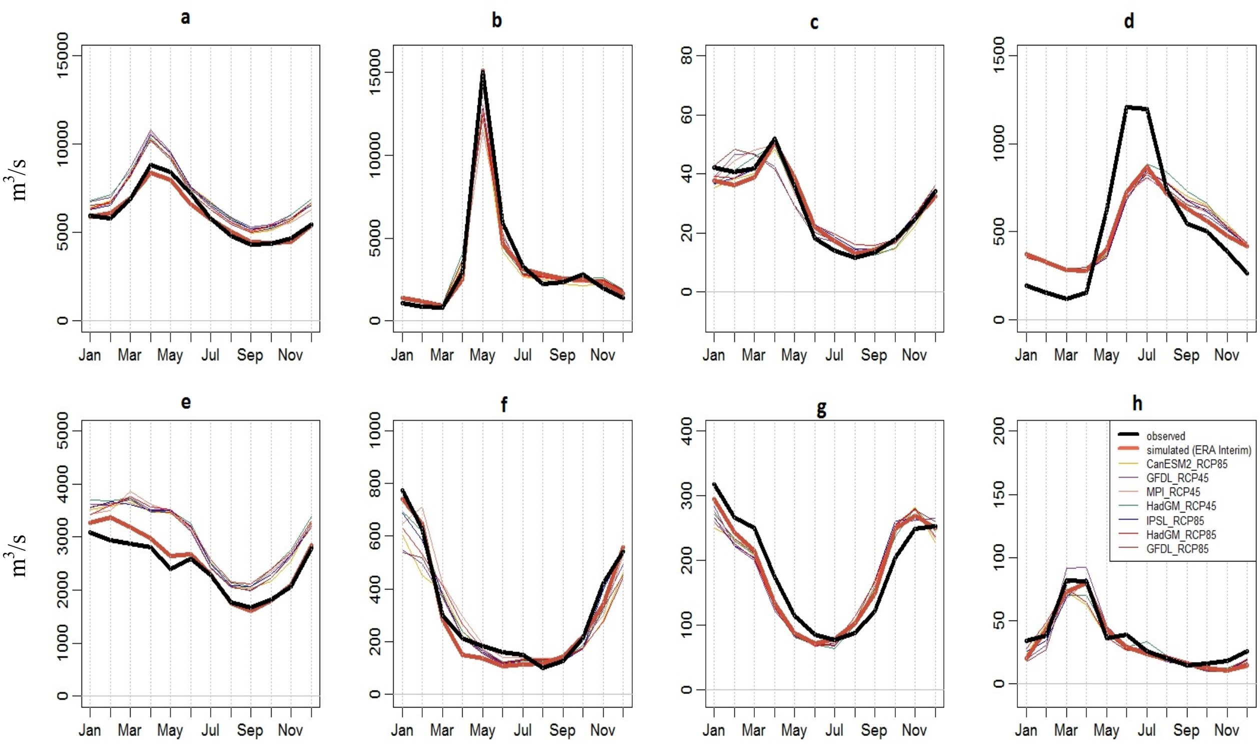

Figure 2.3 The long-term mean annual dynamics observed, simulated with SWIM driven by the WATCH Era Interim data and seven climate models outputs over the reference period 1981-2100 driven by the seven GCM-RCM combinations for the eight case study basins: a) Danube; b) Northern Dvina; c) Emån; d) Lule; e) Rhine; f) Tagus; g) Tay; h) Teteriv

2.5.3 River discharge in the basins under climatic change

The impacts of projected changes in climate on the water resources availability in the case study basins were heterogeneous. Figures 2.4 and 2.5 show the multi-model means (three model runs for RCP4.5 and four for RCP8.5) and the model spreads (minimum to maximum values) for the long-term mean annual discharge at the outlets of the basins in two future periods: 2041-2070 (mid-future) and 2071-2100 (far-future) under two global warming scenarios: RCP4.5, moderate, and RCP8.5, high-end global warming, against the model runs in the reference period.

The significance of changes in the monthly discharge of river basins under consideration was evaluated with the Wilcoxon rank test, at the p=0.05 significance level, comparing reference period to two future periods. Table A3 of Appendix I provides the p-values for each monthly flow in each basin, for two future periods. Please note, that only statistically significant changes are described in this section.

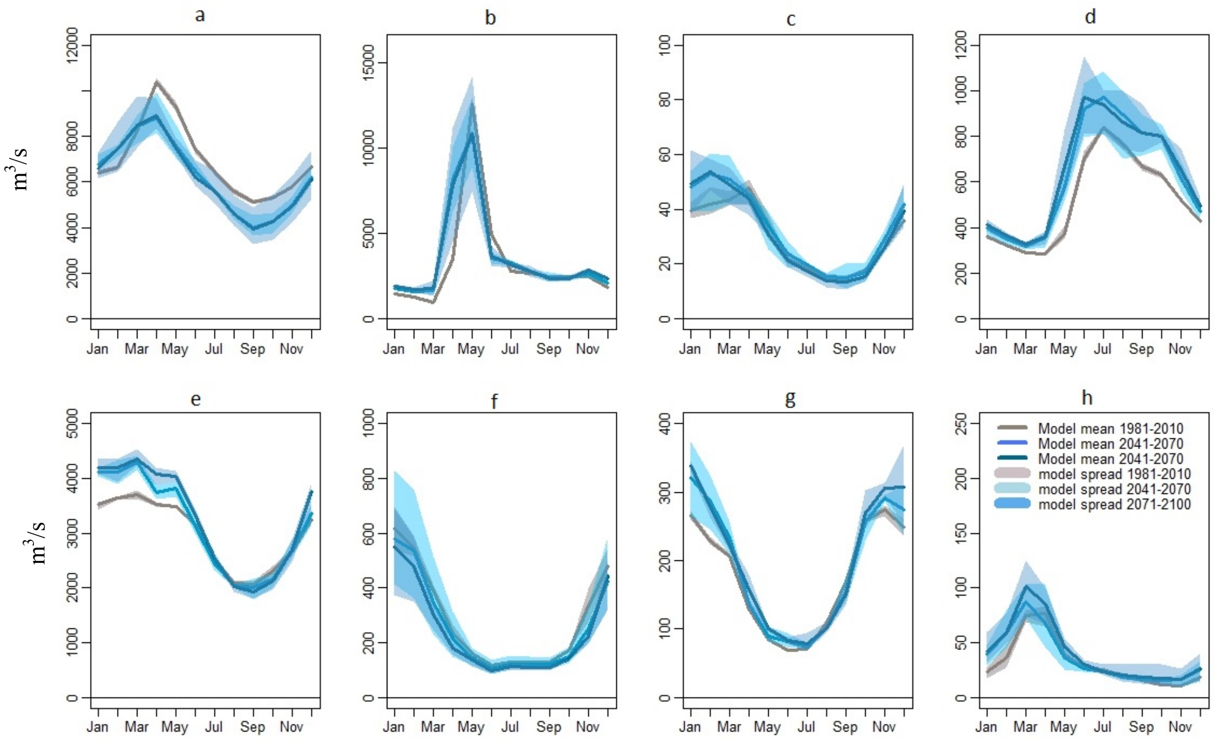

Figure 2.4 Comparison of the long-term mean annual dynamics of discharge in the intermediate and far future time slices with that in the reference period (all - simulated with the SWIM model driven by the climate projections under RCP4.5 scenario) for the eight case study basins: a) Danube; b) Northern Dvina; c) Emån; d) Lule; e) Rhine; f) Tagus; g) Tay; h) Teteriv

An overall statistically significant increase in discharge throughout the year (all months) was found in the Lule River under both warming scenarios and for both future periods. The projected increase in discharge is accompanied by a shift in seasonality; in particular, the peak in discharge is expected to occur approximately one month earlier, shifting from end of July to mid-June. The difference between the intermediate and far future periods is obvious under the RCP8.5 scenario, where the increasing trend is developing further, whereas under RCP4.5 the difference between the far and intermediate future time slices is rather small.

In the Emån, Rhine, Teteriv and Tay rivers a statistically significant increase in the winter and early spring discharge is projected under RCP8.5 in both periods (see Table A3 of Appendix I). The increase is the highest in the Teteriv and Emån rivers: reaching up to +60% in January for the Emån, and up to two times higher in the Teteriv under RCP8.5. In the Rhine and Tay rivers the increase in winter is up to +30% under RCP8.5

by the end of the century. The same tendency is observed in these four basins under RCP4.5, and in January and February the increase (by 20-25%) is statistically significant in all four basins in both periods. Besides, there are seasonal shifts projected for the Emån and Teteriv under RCP8.5, shifting from mid-April to mid-February for the Emån and for the Teteriv from beginning of April to beginning of March.

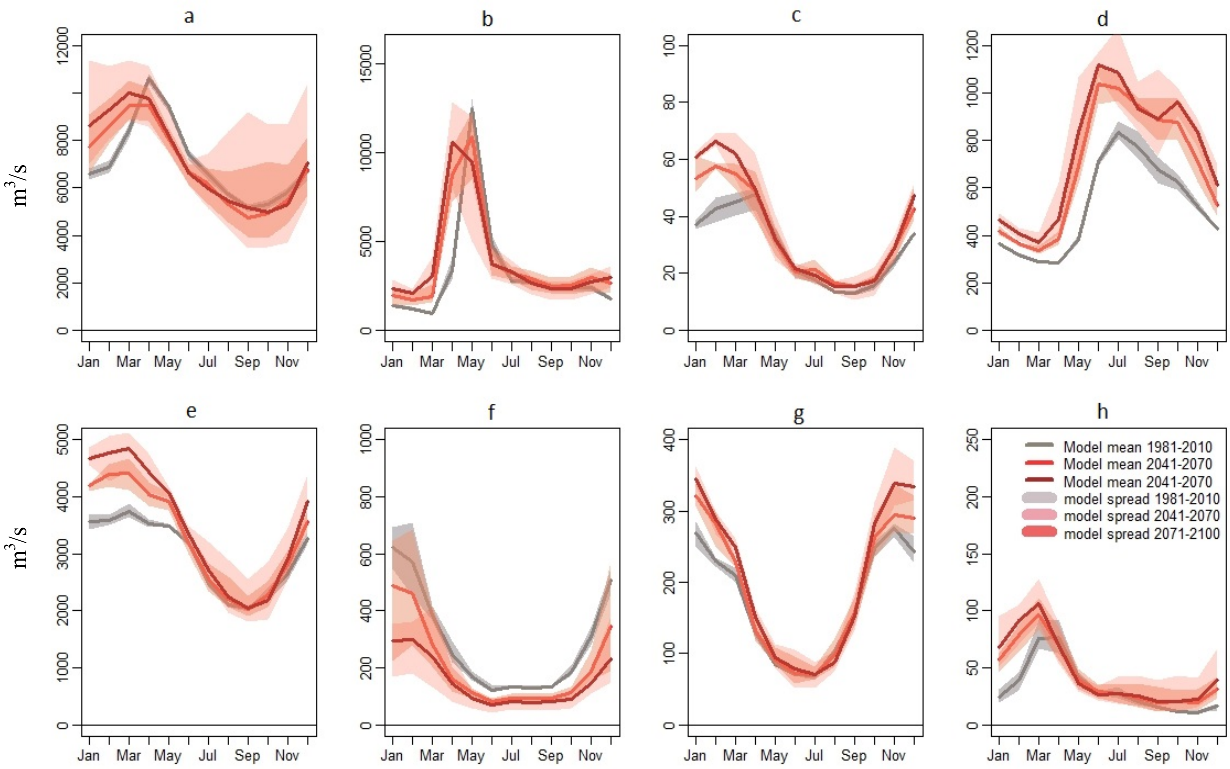

Figure 2.5 Comparison of the long-term mean annual dynamics of discharge in the intermediate and far future time slices with that in the reference period (all - simulated with SWIM model, driven by the climate projections under RCP8.5 scenario) for the eight case study basins: a) Danube; b) Northern Dvina; c) Emån; d) Lule; e) Rhine; f) Tagus; g) Tay; h) Teteriv

In the Danube and Northern Dvina rivers the most notable impacts are shifts in seasonality under RCP8.5 global warming scenario. In the case of the Northern Dvina the spring peak is shifted one month earlier by the end of the century, and the peak discharge period is prolonged in time. Under the RCP4.5 the high flow period begins already in April and reaches its maximum in May. There is also a slight increase in discharge of the Northern Dvina in late autumn and early winter under RCP8.5 for both time slices, and for far future under RCP4.5.

In the case of Danube a decrease in discharge is projected from April until December under RCP4.5, and from April until July under RCP8.5 (based on all model runs). One can see no significant change of the multi-model mean and a large spread of projections from August to December under RCP8.5. Under moderate climate change scenario the peak discharge is shifted from end-of-April to beginning of April and under high-end climate change scenario to mid-March.

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In the southern catchment - the Tagus - an overall decrease in discharge throughout the year was found under both RCP scenarios, based on the multi-model means. The changes are much more pronounced and statistically significant for all months under RCP8.5 in both periods (see Table A3 of Appendix I), resulting in the decrease of discharge by more than 50% throughout the year compared to up to 20% under RCP4.5. The reduction of flows was found to be statistically significant under RCP4.5 only in the low flow period (April - November) for the far future. The model spread was the highest during the high-flow period in January – March for both RCPs. Under RCP4.5 in the winter months some model runs projected an increase, and some decrease, however the multi-model mean still indicates a slight decrease in discharge, and also statistical test showed that this trend is not significant for this RCP. However, also in the reference period the multi-model spread was much larger during the high-flow period in this basin, as can be seen in Figure 2.5 f.

Figures 2.6 and 2.7 provide an overview of the monthly flow variability over the reference and two future periods depicting the monthly flows as box-and-whiskers diagram.

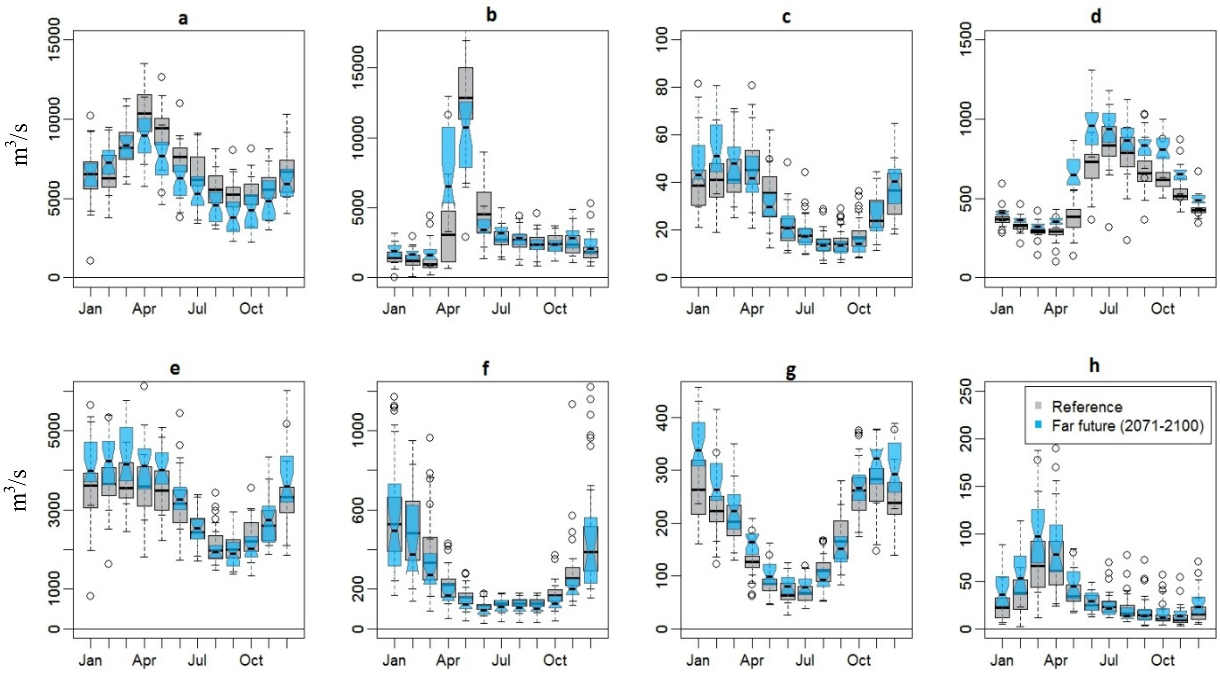

Figure 2.6 Long-term mean annual dynamics of river discharge for the reference, intermediate and far future time slices simulated with SWIM model, driven by the climate projections under RCP4.5 scenario for the eight basins under consideration: a) Danube; b) Northern Dvina; c) Emån; d) Lule; e) Rhine; f) Tagus; h) Tay; i) Teteriv

It is undoubtedly important to know how the mean of the flow will change, but also it is important (especially for water managers) how the inter-annual flow variability would change in the future, and how far it would deviate from the reference conditions. One can observe that the important changes with respect to the inter-annual flow variability are projected for the Northern Dvina River in the high flow period, where the spring peak is shifted one month earlier; for the Tagus, where a decrease of flow is expected throughout the year, and for the Lule, where an increase in discharge is projected for all months. For the rest five basins (Rhine, Emån, Danube, Tay and Teteriv) changes in variability are highest in winter months, and for the Rhine – also in spring.

Table 2.3 provides an overview of changes in the components of the hydrological cycle, in particular in precipitation (PP), actual evapotranspiration (AET), surface runoff (RO) and the Budyko aridity index (which is potential evapotranspiration divided by precipitation) by the end of the century. The aridity index slightly increases under both RCPs in the Danube, and strongly in the Tagus River, especially under RCP8.5. Also PP, RO and AET show a strong decrease in the Tagus under RCP8.5.

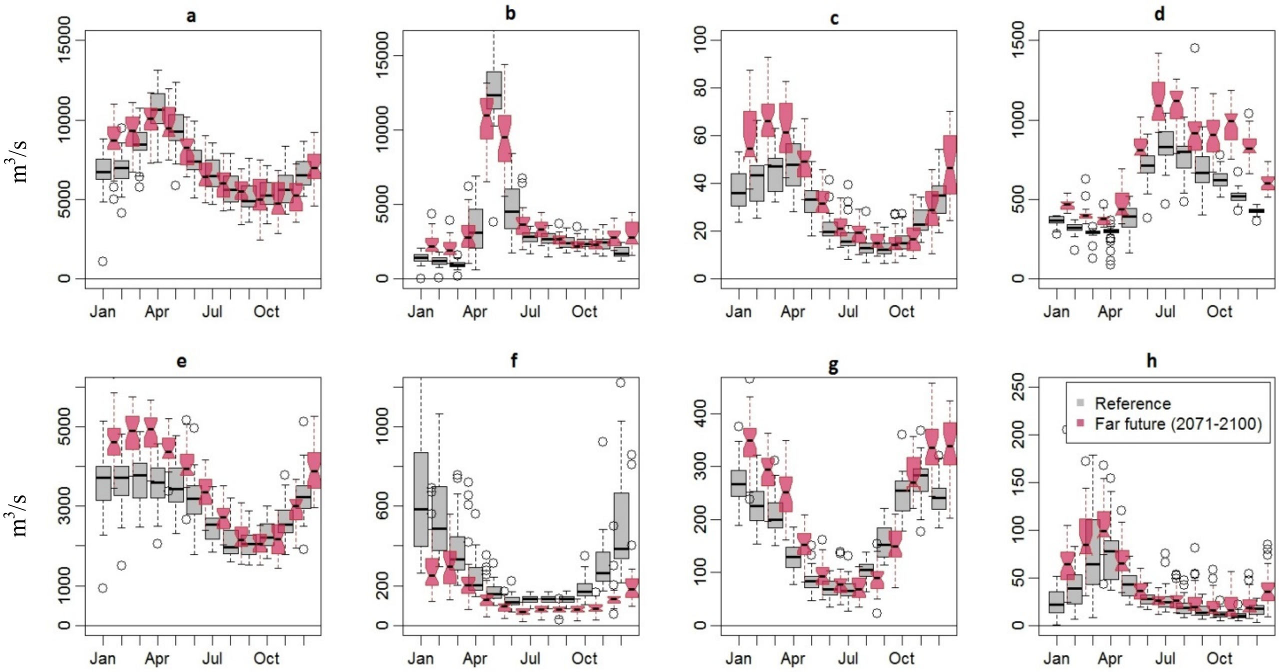

Figure 2.7 Long-term mean annual dynamics of river discharge for the reference, intermediate and far future time slices simulated with SWIM model, driven by the climate projections under RCP8.5 scenario for the eight basins under consideration: a) Danube; b) Northern Dvina; c) Emån; d) Lule; e) Rhine; f) Tagus; g) Tay; h) Teteriv

For the Northern Dvina River the aridity index is increasing only slightly under RCP8.5. On the contrary, the aridity index is decreasing in the Tay. For other basins, the ratio between PET and PP remains practically stable under both climate projections. The increasing trend in precipitation is observed over the Northern Dvina, Tay, Lule, Teteriv and Rhine, under both future warming scenarios, and for the Emån under RCP8.5. Similar patterns were found for runoff, which follows trends in precipitation. Regarding actual evapotranspiration, it is notably increasing in the Northern Dvina and Lule catchments (possibly due to increased temperatures), and decreasing in the Danube and Tagus catchments (subject to low water availability). In other catchments changes in AET are less pronounced, but still even slight changes in AET can lead to significant changes in the water balance, especially in the southern catchments, and therefore they have to be considered.

Table 2.3 Changes in the Budyko aridity index (PET/PP), Precipitation, Runoff and AET in the case study basins

Basin	Aridity Index		PP		RO		AET	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Danube	+	+	-	-	-	minor	-	-
Northern Dvina	minor	+	++	+++	+	++	++	+++
Emån	minor	minor	minor	+	minor	++	minor	+
Lule	minor	minor	+	++	++	+++	+	++
Rhine	minor	minor	+	+	+	++	minor	minor
Tagus	++	++++	-	---	--	----	-	--
Tay	-	-	++	++	++	++	minor	minor
Teteriv	minor	minor	+	++	+++	++++	minor	+

Legend:

++++	>31	++	+11 to +20	minor	-5 to +5	--	-10 to -20	----	<-31
+++	+21 to +29	+	+5 to +10	-	-5 to -10	---	-21 to -29		

2.6 Discussion

This study aimed to provide an assessment of impacts of the projected climate change on streamflow (or: water resources availability) in the eight representative river basins in Europe. For that we employed the eco-hydrological process-based catchment-scale model SWIM, which was set up, calibrated and validated to the observed data at the outlets of each river basin. The SWIM model included water management infrastructure in two case study basins: Tagus and Lule. The impacts of climate change were explored by applying the bias-corrected GCM-RCM climate datasets, obtained in the framework of the IMPRESSIONS project.

The SWIM model was successfully calibrated and validated for all basins, given their climatic, hydrological and physical heterogeneity. However, SWIM has encountered some problems in simulation of the observed discharge in the Lule, Tay and Tagus basins, where anthropogenic influence on discharge was significant. Even when accounting for water management was introduced by implementing major reservoirs in SWIM, like in the cases of Lule and Tagus, the model performance has improved, but still some flow components (e.g. low flow in the Tagus) were not properly met. When conducting climate change impact assessment, the effects of current water infrastructure operations, if their influence is significant, have to be taken into account.

The bias-corrected climate data were used to drive SWIM in the historical period and were tested for their ability to represent the observed discharge dynamics. The results were satisfactory for all basins, except the Rhine and Danube catchments, where the seasonality was met but the systematic overestimation of flows was found. This can be partly explained by the well-known fact that many of the climate models have difficulties in representing climatic conditions over the Alps. Firstly, due to complex orography and relatively coarse horizontal resolution of the climate models to account for the complex elevation patterns it is difficult to represent precipitation over this area, which can lead to the erroneous results. In this case the bias-correction, which allows adjustment of the systematic biases in climatic simulations, would not improve the performance of the simulations. Besides, precipitation may have a strong local variation, which cannot be captured by the 0.5 degree grid of the input data influencing the simulation results.

The climate impacts for the European river basins were heterogeneous. One can distinguish the following statistically significant trends based on the projections: a general increase in discharge in the Northern catchments (Lule, Northern Dvina and Tay), and a strong decrease in the Iberian Peninsula (for Tagus, statistically significant under RCP8.5). The largest differences between the moderate and high-end climate change scenarios were found for the Northern Dvina, Lule and Tagus, characterized by strong inter- and intra-annual variability of flows (see Figure A4 in Appendix I). In the Tagus, the deviations in discharge projected under RCP4.5 were practically within the bounds of the inter-annual flow variability (as indicated by the Wilcoxon signed rank test) until the year 2070, whereas under RCP8.5 a strong decrease in flows, reaching up to -50%, was found. Therefore, these results show that when accounting for the climate change effects on river discharge in the water management strategies it is important to account for the deviations not only in mean annual flows, but also in the intra-annual variability of flows in the future.

In the central and eastern European catchments (Rhine, Danube, Teteriv) as well as in Emån discharge is expected to increase in winter and late autumn. In three northern catchments (N. Dvina, Lule and Emån) and in two Central and Eastern European catchments (Danube and Teteriv) the shifts in seasonality were found at the end of the century under RCP8.5, where the spring peak appears approximately one month earlier. Such effects are possibly associated with the earlier snowmelt due to increased temperatures.

The impact assessment results of current study go in line in terms of general tendencies in Northern and Southern Europe with the results of studies conducted before [55,64,65,72] using the non-calibrated global-scale models. However, zooming in the global or European maps of previous studies for results related to certain river basins is difficult. One former study [55] presented impacts also for five selected river basins, and they are comparable with current results, except for the Rhine (where no statistically significant trends were found before). In general, current results with the validated regional-scale model are probably more credible for all selected eight basins. Still, the similarity of impacts is important, as the previous studies involved different types of models and climate change projections, therefore the trends found in current study can be considered as robust.

Such modelling chains as applied in this paper are associated with different sources of uncertainty, starting from the uncertainty coming with radiative forcing scenarios (RCPs) and finishing with the uncertainty associated with hydrological modelling. The study of Vetter et al. [45] applied the Analysis of Variance ANOVA method to the outputs of nine hydrological models, four RCP scenarios and five GCM models in application to 12 large river basins worldwide. The ANOVA method allowed analysis of the variances in projected changes arising from different sources, in this study – different hydrological models, different GCM and RCP scenarios using subsampling method, as described in Bosshard et al. [93]. They have found that the major uncertainty comes from the GCMs, followed by the RCP scenarios, and the smallest fraction is due to hydrological models. However, for the low flows the uncertainty arising from the hydrological models was more significant.

2.7 Conclusions

Climate change will alter the hydrological regimes of rivers in Europe and will create additional challenges for the already stressed due to extensive anthropogenic activities water resources and aquatic ecosystems. Therefore, the impacts of the projected climate change have to be understood and incorporated into the regional water management strategies to ensure sustainable approach in governing the water systems.

The results of this study indicate an increase in discharge in Scandinavia and Northern Europe, as well as a strong decrease in the Iberian Peninsula. In general, apart from the Tagus and Danube there seems to be no significant changes in the low flow period in other catchments, whereas the flows in the high flow periods in winter and early spring are going to increase across Europe. The shifts in seasonality, in particular shifts of the spring peak discharge to earlier time, were found in the snowmelt driven catchments, like Northern Dvina, Lule, Emån, Danube and Teteriv under RCP8.5, which is associated with the earlier snowmelt.

The differences in deviations between the high-end and moderate climate warming scenarios become evident after the mid-century, where the changes triggered under RCP4.5 level off, and continue to develop further under RCP8.5. The biggest differences between the RCP4.5 and RCP8.5 scenarios were found for the Northern Dvina, Lule and Tagus, where changes under RCP4.5 until the year 2070 were within the bounds of the natural variability of flows in the reference period, and they become more evident only by the end of the century, and under RCP8.5 in both periods.

The global models are useful tools to be applied when general impacts picture is needed at the global and continental scales, and the regional-scale models are absolutely necessary in cases when regional impacts are of interest for certain specific river basins, and also climate adaptation and water management strategies are of interest for them [7]. The local developments in each particular catchment are of a great importance, while considering different scenarios of global warming. Even if the dangerous global warming can be avoided, e.g. by switching to the green sources of energy, the freshwater resources can still be adversely affected by e.g. extension of the hydropower installation [94].

The results of this study go in line in terms of general tendencies with the results of the previous studies, conducted mostly with the global scale models, and therefore the found trends can be considered as robust.

Chapter 3

A idade foi chegando
O cabelo branqueando
Mas o Tejo é sempre novo

(José Viana - Zé Cacilheiro, Portuguese fado)

3 Impacts of changing climate on the hydrology and hydropower production of the Tagus River basin

This chapter is a postprint version and was already published in:

[76] Lobanova, A.; Koch, H.; Liersch, S.; Hattermann, F. F. Impacts of changing climate on the hydrology and hydropower production of the Tagus River Basin. *Hydrol. Process.* **2016** https://doi.org/10.1002/hyp.10966

3.1 Abstract

The Tagus River basin is an ultimately important water source for hydropower production, urban and agricultural water supply in Spain and Portugal. Growing electricity and water supply demands, over-regulation of the river and construction of new dams, as well as large inter-basin and intra-basin water transfers aggravated by strong natural variability of climate in the catchment have already imposed significant pressures on the river. The substantial reduction of discharge is observed already now, and projected climatic change is expected to alter the water budget of the catchment further.

This study addresses the effects of projected climate change on the water resources availability in the Tagus River basin, and influence of potential changes on hydropower generation of the three important reservoirs in the basin. The catchment scale, process-based eco-hydrological model Soil

and Water Integrated Model (SWIM) was set up, calibrated and validated for the entire Tagus River basin, taking into account fifteen large reservoirs in the catchment. The future climate projections were selected from those generated within the Inter-Sectoral Impact Model Intercomparison Project. They include five bias-corrected climatic datasets for the region, obtained from Global Circulation Models runs under two emissions scenario – moderate and extreme ones, and covered the whole century. The results show a strong agreement among model runs in projecting substantial decrease of discharge of the Tagus River discharge and, consequently, a strong decrease in hydropower production under both future climate scenarios.

3.2 **Introduction**

Hydropower is an efficient, low cost and near zero-emissions source of "green" energy, which is becoming increasingly important given the growing role of renewable energy sources in the energy sector [29]. Hydropower production depends strongly on river discharge and its seasonal patterns and hence is very sensitive to shifts in the components of the hydrological cycle [95]. Projected changes in climate will influence the hydrological cycle, altering runoff conditions [2] in many regions across Europe as well as globally, putting the reliability of hydropower production and the suitability of established reservoir management strategies in question. As discussed by Schaefli [96], a number of assessment studies addressing reservoir and hydropower vulnerability to projected climate change at the local [97–99], continental, and global scales [100,101] exist, but they are limited when compared to the total number of papers tackling the hydrological impact of climate change. Schaefli [96] also identified the necessity to perform studies at scale of single reservoirs, with the employment of hydrological models coupled with reservoir models, and possibly, with the energy market models.

Future climate projections for the Iberian Peninsula and the Mediterranean area show a general decrease in precipitation and an increase in air temperature [2,102–104]. Owing to the availability of long-term observations in the Iberian Peninsula, there is a number of studies conducted, aimed to detect climate change signals in the region, e.g. the analyses of Gallego et al. [105] and De Luis et al. [106]. They found that over five decades, until the year 2005, the precipitation patterns of the Iberian Peninsula have changed, showing an increase in precipitation in autumn and decrease in winter, spring, and summer. Further, studies of Guerreiro et al. [56] and Gonzales-Hidalgo et al. [107] specified that precipitation in the Tagus River basin has decreased in February, March and June, and increased in October. Lorenzo-Lacruz et al. [108] and [109] indicated that the severity, magnitude, and duration of droughts in the Iberian Peninsula have increased over the period 1945-2005 and river discharges, including that in the Tagus River basin, has significantly decreased.

The so-called "eighties effect", i.e. the observed downward trends in the stream discharges of the rivers in Spain since 1980 has also been widely discussed in literature [110–113]. Comparing the periods 1980-2005 and 1960-1980, the study of Martinez [112] indicated a decrease in discharge by 47% in the headwaters of the Tagus River, at the inlets of the Buendía and Entrepeñas reservoirs. However, no clear evidence is provided to whether this trend can be attributed solely to the recent changes in climatic conditions or to the changes in land use and extensive water management practices in the region [109,114,115].

The projections of climate change impacts on hydrological processes on the scale of the Iberian Peninsula [28,103,116–118] as well as of single river basins within the region [56,57,119,120] has been widely discussed in literature. The work of Kilsby et al. [57] suggests a decrease of 50% in discharge of the Tagus River and approximately 39% of the Guadiana River by the year 2100 under the high emissions scenario (A2). A more recent study of Diogo et al. [121] projects a decrease of precipitation between 10% and 18% by 2100 at one tributary of the Tagus River, the Zezero River (Portugal). They conclude, that these changes would result in a reduction of inflows into the reservoir Castelo do Bode (Portugal) between 20% and 34% under the moderate B2 and high A2 emissions scenarios.

The hydrological impacts of the projected climate change in the Spanish part of the Tagus River basin were investigated and presented in the series of studies performed by CEDEX [122,123]. They simulated the impacts of the climatic change on the natural regime of the Spanish part of the Tagus River, until the Cedillo reservoir with distributed rainfall-runoff model SIMPA [124] and considering the extensive water infrastructure in the basin with application of the optimization model OPTIGES [122,123]. They have fed the time series of natural discharge projections into the optimization model OPTIGES to simulate the reservoirs in the basin. Their findings indicate a decrease in the natural discharge of the Tagus River (Spanish part of the catchment) of 35% under A2 and 15% under B2 scenario conditions by the end of the 21st century. However, it is not specified in the report if their methodology explicitly accounted for the mutual influences of the reservoirs on each other, as well as no detailed results are provided for the performance of the water infrastructure under climate change. In the Tagus Basin Management Plan [103] it is specified that there is a need in the more detailed studies of the hydrological processes and water infrastructure to enhance the optimal adaptation management strategies.

The work of Linares and Khan [125] provides information on the impacts of climate induced water shortages on the energy sector in Spain. Their study is based on calculation of the energy production coefficient which links the runoff changes and level of produced energy in all river basins in Spain. As the detailed investigation of the reservoirs systems dynamics in the Spanish River basins was beyond the scope and methodology of their study, they employed a top - down approach, without the consideration of the reservoirs network of the basins, but only considering single virtual reservoir with a hydroelectric plant of the total installed capacity in the basin.

It should be noted that all the aforementioned studies have addressed the hydrological impacts of climate change only for the specific parts of the Tagus River basin (subbasins or only one national part). Firstly, this study closes this gap by providing the picture of potential impacts on the hydrological processes of the entire Tagus River basin under moderate und high-end climate change scenarios, employing the latest global warming scenarios. Further, the methodology applied explicitly integrates the topology of the reservoirs system in the basin by coupling the conceptual reservoir module with the process-based hydrological model. This allows us to represent the reservoir management processes, their influence on the river discharge and on each other. This study aims to show that the integration of reservoirs and water management processes into a hydrological model is essential for achieving a realistic physical representation of the hydrological processes in a highly managed river catchments.

Finally, the insights to the impacts of climatic change on the hydropower production and adaptive potential of three representative reservoirs in the Tagus River basin of different sizes and purposes of use were provided. Such understanding is essential for the water and energy resources planning as well as for defining the adaptation strategies for the Tagus River basin. The results can be seen as a reference also to the other rivers in the Iberian Peninsula and the Mediterranean region which have similar climate and hydrological conditions and therefore similar reservoir operation rules.

3.3 **Case study**

3.3.1 Tagus River basin

The Tagus River has a total length of approximately 1000 km, a total drainage area of 80 000 km^2, and a mean discharge of 500 m^3s^{-1} at the outlet. One of the most important rivers on the Iberian Peninsula, it is the main water source for a number of large cities (e.g. Lisbon, Madrid), as well as for agricultural and industrial uses, and hydropower production [126].

The climatic conditions vary from Mediterranean in the eastern part to Atlantic in the western part of the basin. The precipitation patterns show high variability, with headwaters receiving around 1100 mm yr^{-1}, and middle reaches in the southern part only 450 mm yr^{-1}. The estimated mean annual potential evapotranspiration at the central reach on the Spanish side is 800 mm yr^{-1} [127]. There is a clear seasonal and monthly variability in the climate of the Tagus River basin with a wet period from October to April and a dry period from May to September [57]. Sequentially, the discharge maxima occur from December to March, reaching a peak in February and the discharge minima are observed in August [128].

The Tagus River basin is one of the most heavily regulated basins in the Iberian Peninsula [127]. Due to the increasing number of drought events in the region since 1960 [129] and growing water and electricity demands, an extensive construction of reservoirs and a network of abstraction channels took place in the Tagus River basin. Nowadays, there are more than 40 large reservoirs in the basin with a capacity of more than 15 hm^3. The total capacity of all reservoirs in the basin is 14 500 hm^3, of which 12 500 hm^3 belong to Spain, and the rest to Portugal. Such extensive flow regulation has changed profoundly the morphology of the river over the last fifty years, with large volumes of sediments being trapped in the reservoirs. The initial braided character of the river has significantly decreased over time leading to the straitening of the channel [130]. The reservoir operation rules in the Tagus River basin depend on the strong seasonal variability of flows: they store the water during the high flow periods in winter and discharge water during the summer, when water is needed for irrigation and to homogenize hydropower production over the year. In 1978, a water transfer from the Tagus River basin to the Segura River basin was organized to overcome the virtually constant water scarcity in the latter basin, and to ensure agricultural production and urban water supply there. The Tagus River basin was intended to supply 600 hm3 annually during the first implementation phase, and up to 1000 hm^3 in the second [110]. Since the start of the transfer, the Tagus was able to supply on average only 331 hm^3 of water annually [108].

The discharge of the transboundary rivers at the border between Portugal and Spain is regulated by the “Albufeira” treaty signed in 1998 [131]. This agreement prescribes, depending on the current climatic conditions, minimum discharge regimes at the border to Portugal. The “Albuferia” treaty came in power to sustain water volumes reaching Portugal in the face of expansion of the Spanish water infrastructure and large inter-basin transfers according to the Spanish National Hydrological Plan 1993 [132]. The Albufeira treaty was modified in the year 2008, after severe drought hit Spain and Portugal in 2005 and the discharge of the Tagus River at the border was significantly decreased, partly also due to increased water volumes transferred to the Segura catchment [132].

3.3.2 Reservoirs under consideration

This study focuses on three representative reservoirs in the Tagus River basin: two in Spain i) Gabriel y Galan and ii) Buendía, and one in Portugal: iii) Fratel. The two reservoirs in Spain are located in the headwaters with large storage capacities and fall heights of hydropower plant, both serving mainly for hydropower production. The Fratel reservoir is located at the main stream of the Tagus River; it is of the run-of-the-river plant type, with a low life storage, low fall height, and high discharge used solely for hydropower production. The reservoirs were selected based on their size, importance and type. Table A5 in Appendix I summarizes the technical characteristics of the three reservoirs and hydropower plants installed. The efficiency of the installed turbines was not known and was estimated from the characteristics of the hydropower plants installed: capacity of the hydropower plant, maximum discharge and water level. Figure 3.1 presents the geographical location of three reservoirs. The Tagus-Segura water transfer takes place downstream of the Buendía reservoir.

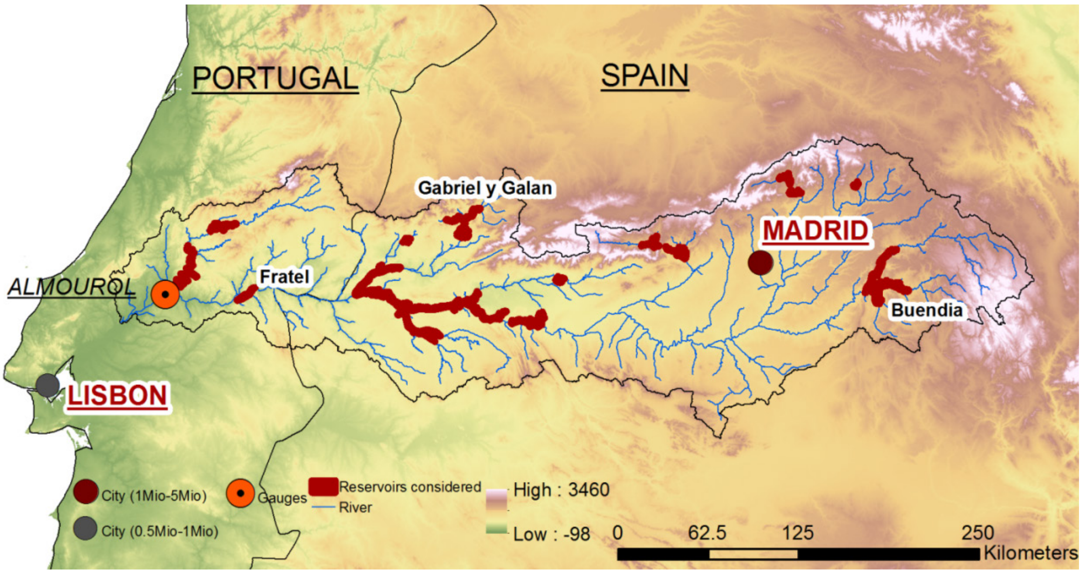

Figure 3.1 The Tagus River basin until the gauge Almourol, reservoirs included into modelling framework and location of the three reservoirs under consideration

3.4 **Methods and data**

The eco-hydrological process-based model Soil and Water Integrated Model (SWIM) was set up, calibrated and validated, including 15 major reservoirs, for the Tagus basin until the gauge Almourol in Portugal. Reservoir management and hydropower production were simulated by the SWIM reservoir module [85]. The Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) climate projections under two global warming scenarios were fed into the SWIM model and simulated over the entire period 1950-2100. The mean annual long-term changes in the water inflow into reservoirs and hydropower production for two selected future time slices: 2021-2050 and 2070-2099 were compared to the reference period 1971-2000.

3.4.1 SWIM Model

The semi-distributed, eco-hydrological, process-based model SWIM is based on two previously developed models: SWAT'93 [133] and MATSALU [42]. The detailed description of the model structure and components can be found in in Krysanova et al. [41]. The SWIM model can be seen as an assemblage of numerical representations of physical processes of the hydrological cycle and related processes including vegetation growth, nutrient cycling, and erosion. These physical processes are mathematically interpreted with intermediate levels of complexity and form four main modules of the model: hydrological, groundwater, biogeochemical and plant growth modules. The model operates on a daily-time step producing time series of discharge, nutrient flows and sediment transport as well as crop yield, and uses climatic, land use, topographic and soil datasets as input. The forcing climatic datasets include daily precipitation, solar radiation, relative humidity, and minimum, maximum and average daily temperatures.

The topographical map of a catchment serves as a basis to create a subbasin map, which is later intersected with land use and soil maps to identify the Hydrological Response Units (HRU) - areas within each subbasin, with a unique combination of land use and soil type. Identical HRUs (also called hydrotopes), i.e. those with the same land use and soil types in a subbasin, are assumed to have the same hydrological "behaviour" and are later combined into hydrotope classes within each subbasin. The components of the hydrological cycle, nutrient cycling and sediment loads are calculated at the HRU level and the lateral flows are aggregated at the level of sub basins. The flows of water, nutrients and sediments are then routed through the basin, using a conceptual representation of the open channel hydraulics – the Muskingum method, taking into account transmission losses. Significant number of the successful calibration and validation stories of the SWIM model applications has proven the adequacy of this model to simulate the hydrological (e.g. Hattermann et al. [5,134]), biogeochemical as well as hydrochemical (e.g. Huang et al.[135]) and crop growth (e.g. Liersch et al. [79]) processes in river basins of various sizes, geographical locations and with different data availability (see e.g., Aich et al. [78,82]). A thorough description of the success studies, as well as failure cases can be found in Krysanova et al. [43]. The model took part within the frame of the ISI-MIP project in the model and impacts intercomparison exercise (e.g. Vetter et al. [45])

3.4.2 Reservoir Module

The SWIM reservoir module is a conceptual representation of the reservoir management processes, developed and described by Koch et al. [85]. The reservoirs in the river basin are integrated into the subbasin map as separate specific "subbasins" within the SWIM model. During the simulation the stored water volumes, inflow and outflow rates, hydropower production, precipitation, evaporation and seepage are calculated for each reservoir on a daily time step. The operation rules of reservoirs are represented within the reservoir module as one of the following three management options: i) target of the daily minimum discharge downstream, constrained by the minimum and maximum values of reservoir volumes; ii) target of daily minimum discharge based on the requirements for firm hydropower production; iii) daily release, depending on the water level. To set up the reservoir module, information on the volume – discharge – water level relationship (also called "characteristic curve") of the reservoir, minimum and maximum volumes, minimum daily discharges and withdrawals should be provided. In order to simulate hydropower production (HPP), the following characteristics of the hydropower plant are required: fall height, turbine flow capacity, maximum installed capacity and the efficiency of the turbines.

The hydropower produced per day at the hydropower plant is calculated as following:

$$P = (\eta \cdot \rho \cdot Q \cdot h \cdot g) * 24/1000 \qquad [kWh]$$

where η is turbine efficiency, ρ is water density, Q is discharge, h is water head and g is the acceleration due to gravity.

3.4.3 Input Datasets

For the model set-up, the Digital Elevation Model (DEM) of the Tagus River basin in 90m resolution was obtained from the Shuttle Radar Topography Mission (SRTM) [36] of the Consultative Group for International Agricultural Research (CGIAR) Database. The land use data were provided by Coordination of information on the environment CORINE database and the soil data was extracted from the European Soil Data Centre [37].

The gridded climate WATCH Forcing Data (WFD) [38] based on ERA40 re-analysis product [136] were used to calibrate and validate the SWIM model against observed data at the Almourol gauge, provided by the SNIRH database of the Portuguese Ministry of Environment over the period from 1984 to 1999. The WATCH provide synthetically generated climate time series for the whole globe on a 0.5 degree grid, covering the entire 20th century. The WATCH climate series are corrected to observations, and contain all climatic variables needed to set up the SWIM model. A detailed description of the creation, correction procedure and limitation of this dataset can be found in the work of Weedon et al. [38]. The usage of such synthetically generated climatic datasets has become a common praxis in hydrological modelling, since the observed climate datasets required to set up and run models are often not freely available, are too short or inconsistent, or do not even exist. In the case of the Tagus River basin, an extensive network of climate stations exists for both Portugal and Spain. However, the Portuguese dataset contained serious gaps and the number of stations in Spain containing long-term observations was not sufficient to calibrate the SWIM model. Additionally, only few stations within the basin provided observations of solar radiation.

The volume – surface area – water level relationship for reservoirs as well as information about water abstraction was obtained from the Tagus River Basin Management Report provided by the Ministry of Environment of Spain [137] and from the SNIRH database for the Portuguese part. The information on observed inflows, outflows, and volumes in the reservoirs, used for calibration and validation of selected reservoirs, was provided by Centro de Estudios Hidrográficos del CEDEX database.

3.4.4 Calibration and validation

The SWIM model was calibrated and validated against the observed discharge data series on a monthly time step at the gauge Almourol. As the assessment of future changes was performed for the long-term mean monthly values of simulated discharge, the calibration and validation of the model was performed on the monthly time step.

Two criteria of goodness of fit between the observed and simulated discharges were used to evaluate the model performance: the Relative Volume Error, RVE, and the Nash-Sutcliff Efficiency [138], NSE.

$$RVE = \left(\frac{\overline{Q_{sim}}}{\overline{Q_{bs}}} - 1\right) \cdot 100$$

$$NSE = 1 - \frac{\sum_{t=1}^{T}(Q_{obs} - Q_{sim})^2}{\sum_{t=1}^{T}(Q_{obs} - \overline{Q_{obs}})^2}$$

Where Q_{obs} – observed monthly discharge, $\overline{Q_{obs}}$ – long-term mean of observed monthly discharge, Q_{sim} simulated monthly discharge and $\overline{Q_{sim}}$ – long-term mean of the simulated monthly discharge.

The RVE is the total deviation between the observed and simulated volumes of water discharged, expressed in percent, and the NSE is an efficiency coefficient, which relates a sum of squared differences between the observed and simulated discharges to the variance of the observed values of discharge. The RVE coefficient can vary from -100 to positive infinity, where 0 indicates a perfect fit, and the NSE coefficient varies from negative infinity to 1.0, where 1.0 indicates a perfect fit. The specific limits for both criteria, which correspond to a "good" performance of model can be found in the work of Moriasi et al. [90].

The calibration was conducted at the first stage without the implementation of the reservoir module, until the Almourol gauge for the following periods: calibration from 1987 to 1993, and validation for 1994-1999. The calibration was carried out manually, with sequential refinement with the automatic calibration tool PEST [139]. The calibration included refinement of the seven parameters which were constant over the entire basin: evapotranspiration correction coefficient, base flow factor, groundwater delay factor, two routing coefficients, Manning coefficient, and saturated conductivity correction coefficient.

At the second phase, fifteen largest reservoirs were selected based on their size (more than 40 hm^3) and degree of river flow alteration, parameterized, and included in the model through integration of the reservoir module (locations of reservoirs presented in the Figure 3.1). Firstly, the monthly inflows of water volumes into each reservoir were calibrated and validated. At this stage the initial set of values obtained during the first step of calibration was used as a starting set to calibrate the sub-catchments of each of the reservoirs in the headwaters. To calibrate the inflows into the reservoirs the manual tuning of five parameters: evapotranspiration correction coefficient, saturated conductivity correction factor, two routing coefficients and groundwater delay factor was performed. The calibration parameters did not show significant deviations in most parts of the catchment, except in the Buendía and Entrepeñas reservoir sub-catchments, where the values were notably different. Then the simulated volumes of water outflow and stored volumes of water for each reservoir were compared with measured data, and adjusted depending on management type it has been assigned to: e.g. Gabriel y Galan was identified as management type one, and Buendía and Fratel as type two. The calibration of the reservoir outflow and stored volumes for management option two was performed on a monthly time step and included assignment of the target minimum discharge downstream (HPP requirement) and adjustment of the special annual cycle coefficient which regulates the percentage of volume that can be discharged in a given month. For the management option one calibration included introduction of three operation thresholds: minimum release rate and minimum and maximum volumes of water stored in a given month. By applying characteristic curves of each given reservoir the water depth, release depending on the water depth and wetted area for each reservoir at each time step were obtained. At the third step, the entire catchment area (excluding the sub-catchments of the headwaters reservoirs) was manually re-calibrated, taking the discharge at the Almourol gauge, as well as at the inlets of the reservoirs located at the Tagus River itself as objective functions.

The Tagus-Segura water transfer was represented as a direct water withdrawal downstream of the Buendía and the Entrepeñas reservoirs. The daily time series of transferred water volumes were obtained from the CEDEX database over the period 1987-1999. While for the reference period the observed daily diversions over 1987-2000 were applied, for the future simulations the mean monthly withdrawal rates calculated over the whole 1987-2000 period were used, as the estimation of the development of the Tagus-Segura water transfer in the future was beyond the scope of this study. For the years 1979 when the transfer began to 1986, which were not covered by daily observations, mean monthly withdrawal rates estimated over 1987-2000 was applied.

3.4.5 Climate Projections

In this study climate projections from the ISI-MIP project were used. As described in Warszawski et al. [49], the project aims to provide cross-sectoral climate change impact assessment and intercomparison using multiple impact models driven by different Representative Concentration Pathways (RCPs) [16] and Shared Socioeconomic Pathway Scenarios (SSPs) (IPCC 2000). The RCPs represent a set of global warming scenarios which were developed in 2007 to substitute the climate scenarios described in the Special Report on Emissions Scenarios SRES (IPCC 2000). The RCPs include four general trajectories of greenhouse gases emissions, concentrations and land use emissions until the year 2100, covering a span of increase in radiative forcing from 2.6 to 8.5 W/m^2.

Hempel et al. [22] describe the ISI-MIP scenarios, which are based on the five GCM simulation results from the Coupled Model Intercomparison Project (CMIP5): i) HadGEM2-ES, ii) IPSL-CM5A-LR, iii) MIROC-ESM-CHEM, iv) GFDL-ESM2M and v) NorESM1-M. Instead of using the regional climate model for a dynamic down scaling the ISI-MIP scenarios employ statistical method of downscaling and bias-correction ensuring the preservation of the warming trends. At first, the GCM outputs were bi-linearly interpolated into a half-degree grid of the WATCH Era 40 dataset, and then bias-corrected using the WATCH data as reference. The bias-correction was done in two steps. Firstly, the monthly variability and means of climatic variables were multiplied by a constant factor to correct for the long-term differences between the observed and simulated monthly mean data. Then daily data variability around their monthly means was corrected by applying grid-cell specific transfer functions to match the observed data variability around their specific means. A more detailed description of this bias-correction method and its limitations can be found in Hempel et al. [22].

For this study we selected the ISI-MIP climate projections under two global warming scenarios RCP4.5 and RCP8.5. The RCP4.5 refers to global temperature increase from 1.7°C to 3.2°C until 2100 and is considered to be a "moderate" scenario, whereas RCP 8.5 is an extreme scenario, corresponding to warming levels from 3.2°C to 8°C until 2100 [140]. All future climate projections were provided as continuous daily datasets of climate parameters over the whole period of 1950-2100.

3.5 Results

3.5.1 Model calibration and validation

- Outlet

Simulation of the whole basin, after calibration without implementation of water management, for the period 1984-1999 resulted in NSE of 0.87 and RVE of -2.42% for the calibration period, and NSE 0.89, and RVE 6.9% for the validation period.

After implementation of the reservoir module and calibration of all fifteen reservoirs, the final NSE and RVE for the calibration and validation periods at the gauge Almourol were 0.86 and -7.2% and 0.89 and 6.1%, respectively (see Figure 3.2a and 3.2b). Values of the NSE coefficient on a daily time step were 0.75 for the calibration period and 0.8 for the validation period. Although the SWIM model was able to reproduce the discharge at the outlet accurately, even without consideration of water management, the long-term average monthly dynamics (Figure 3.2c) clearly show that the effects of water management, in particular the increase in summer and autumn flows and the decrease in winter flows, are much better represented when the reservoir module is included. The long-term annual dynamics for the simulated discharge resulted in R^2 0.93 without implementation of the reservoir module and 0.96 with. The good performance of SWIM without implementation of the reservoirs was only achieved because the water management effect was compensated by specific parametrization of the model, e.g. by adjusting infiltration and groundwater return flow processes. This means that water storage without considering water management does not take place in the artificial surface reservoirs but rather in the aquifers. In this set-up the groundwater delay factor (in days) for the simulation without reservoirs was twice as high as that of the simulation with reservoirs (55 days). Also, the Manning coefficient for the overland and channel flow was one and a half times higher than the one used in the simulation with including reservoirs, slowing down the overland flow.

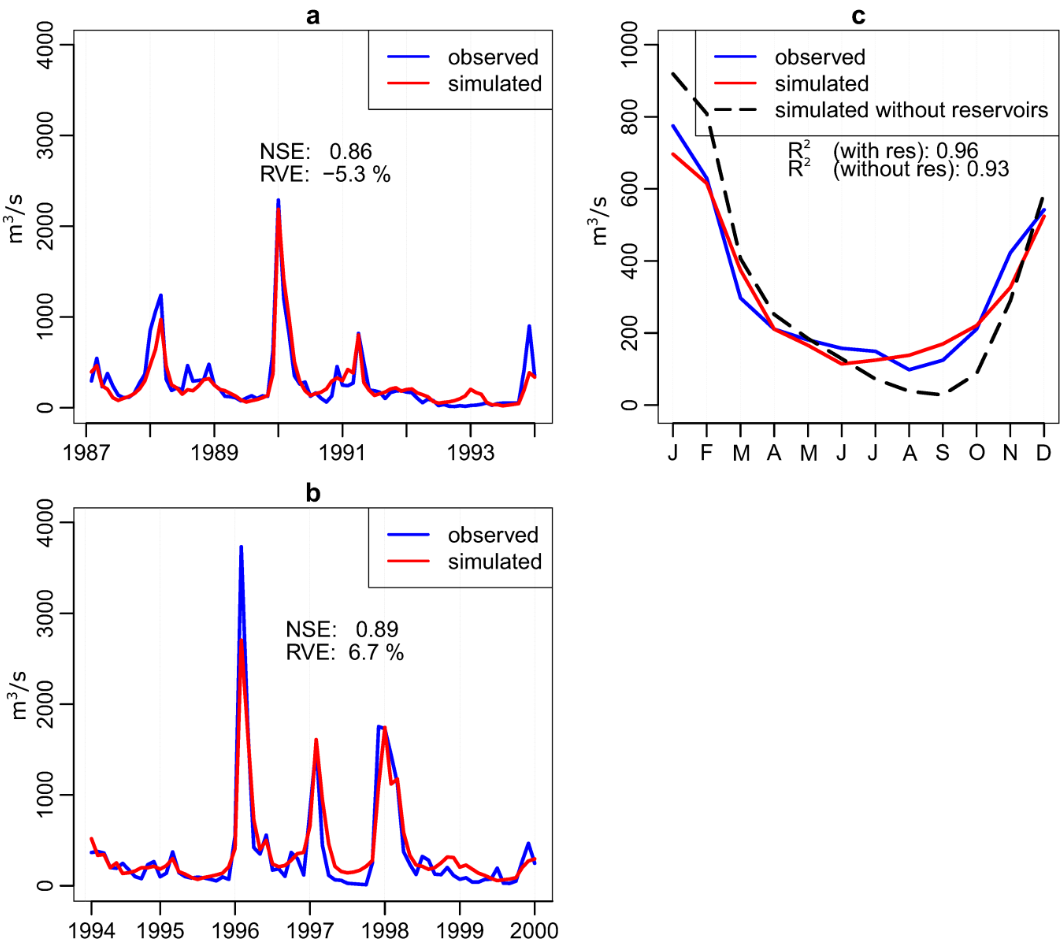

Figure 3.2 Calibration (a) and validation (b) results for the SWIM model at the Almourol gauge with the implementation of the reservoirs; and observed long-term average seasonal dynamics of the Tagus River over period 1987-1999 vs. simulated with SWIM model, with and without implementation of reservoirs (c)

The increase in the RVE value between the calibration and the validation periods can be explained by an increase in water withdrawals for irrigation between the two time periods because, as described above, in this model the extensive network of irrigation channels was not taken into account.

1 Reservoirs

Table 3.1 presents the calibration and validation results for the three reservoirs selected for this study. In general, the SWIM model including the reservoir module was able to reproduce the inflow, outflow and volume dynamics of the reservoirs. The lowest NSE was obtained for the simulation of the inflows into Buendía reservoir during the calibration period, and the largest RVE error was obtained for inflows into the Gabriel y Galan reservoir during the validation period. The latter can be explained by developments in the water withdrawals upstream of the reservoir over the simulation period. As the Fratel reservoir belongs to the run-of-river type, its volume variability was minimal and was not evaluated, whereas the water levels and outflow volumes were successfully represented by the SWIM reservoir module. Also, in case of the Fratel reservoir, the inflow data for the validation period were absent, and could not be evaluated.

Table 3.1 Results of calibration (1987-1993) and validation (1994 -1999) of water inflows, outflows and stored volumes of the selected reservoirs

Reservoir	**Period**	**Goodness of fit**					
		Inflow		**Volume**		**Outflow**	
		NSE	**RVE**	**NSE**	**RVE**	**NSE**	**RVE**
Buendia	Calibration	0.39	-0.7	0.78	-4	0.5	-19.3
	Validation	0.76	4.2	0.78	11.1	0.51	-2.4
Gabriel y Galan	Calibration	0.91	6	0.69	-6.5	0.3	-6
	Validation	0.82	19.5	0.49	-11.2	0.65	10.7
Fratel	Calibration	0.79	0.3	-	-	0.79	0.1
	Validation	-	-	-	-	0.88	11.9

As the observed data series on the hydropower produced were not available to validate the rates of the hydropower produced simulated by SWIM the comparison between the simulated and the calculated hydropower produced was performed. Using the observed outflow rates and estimating the fall heights from observed daily volume values (from characteristic curves) obtained from the CEDEX database the monthly average “observed” hydropower production rate was calculated and compared it to the one produced by SWIM. On average, the percentage deviation from the observed values were: for Gabriel y Galan the SWIM was overestimating the hydropower produced by 12%, for Buendía underestimating by 7% and for Fratel underestimating by 10% over the entire period of 1987-1999.

3.5.2 ISI-MIP climate projections for the Tagus River basin

Figure 3.3 presents trends (moving averages over subsets of 30 years with respect to reference period 1971-2000) in temperature and precipitation of the ISI-MIP climate projections for the Tagus River basin for RCP4.5 and RCP8.5 scenarios. The increase in temperature projected by selected models is between 1.7°C and 3.7°C for RCP4.5, and between 2.5°C and 6.2°C for RCP8.5 by the end of the 21st century.

Regarding precipitation, all climate models agreed on a decrease in precipitation in the Tagus River basin by the end of this century for both scenarios. Projections for the RCP8.5 scenario for the mid-century are rather uncertain, as two models are projecting an increase and three models a decrease in precipitation.

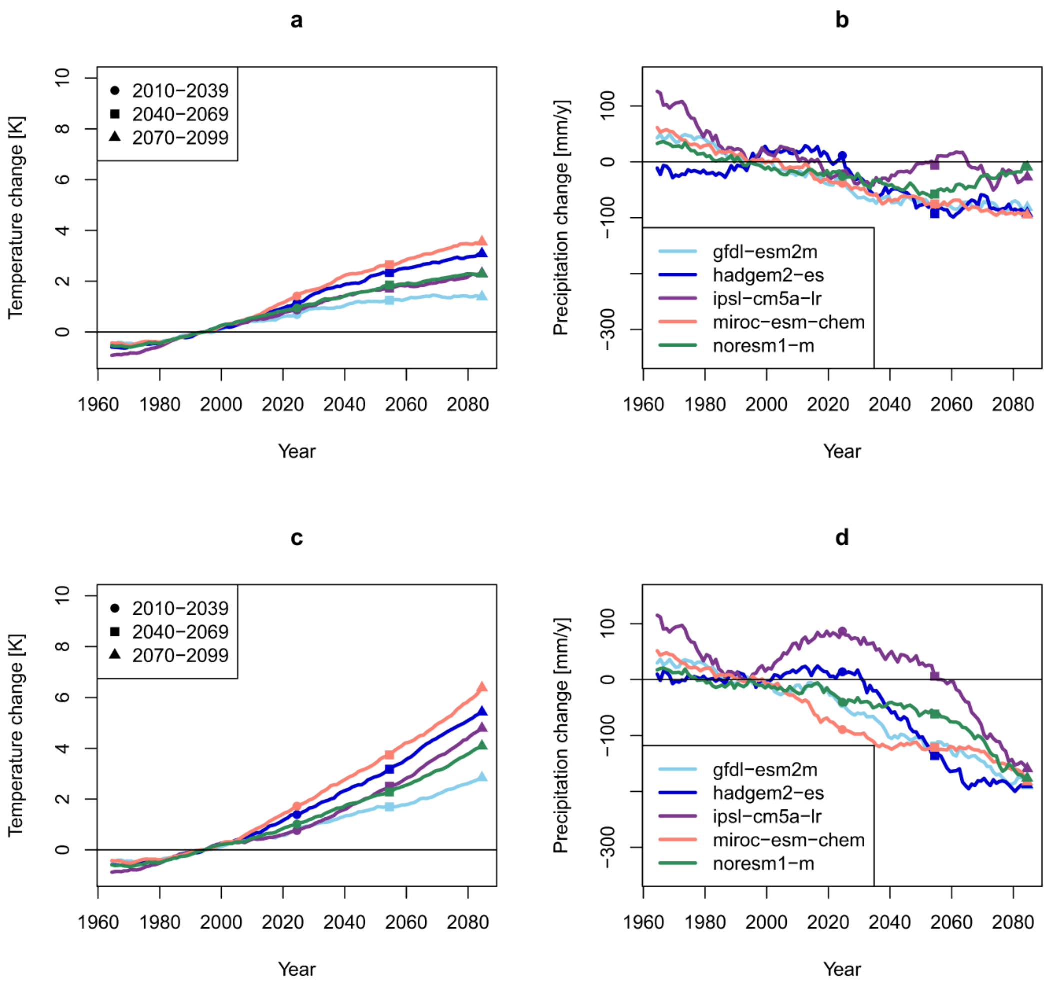

Figure 3.3 Annual projected trends (running mean over 30 years with respect to reference period 1971-2000) in temperature and temperature for RCP4.5 (a, b) and RCP8.5 (c, d) for the Tagus River basin

3.5.3 Testing the ability of climate scenarios to represent the past dynamics of inflows into reservoirs and at the Almourol gauge

In the next step, the ability of SWIM driven by reference climate datasets produced by climate models to simulate the discharge at the outlet as well as inflows into the reservoirs (1987-1999) was tested. Figure A6 of the Appendix I presents the long-term average annual discharge dynamics of the Tagus River at the Almourol gauge over the calibration and validation period for observed, simulated with WATCH and simulated with reference climate dataset and Table A7 represent the R^2 values of fitting between those. Figure 3.4 presents observed, simulated with WATCH and simulated with the reference climate dataset long-term average seasonal dynamics of the inflows into the three reservoirs. The dynamics are well represented, yet in the case of Buendía and Fratel reservoirs the discharges in January and February as well as in early spring are slightly overestimated in simulations driven by all five GCMs, and for the Gabriel y Galan reservoir a disagreement between models in January and February was found. The highest deviation can be seen in the simulation driven by the IPSL-CM5A-LR model, which also showed the “wettest” behaviour in Figure 3.3.

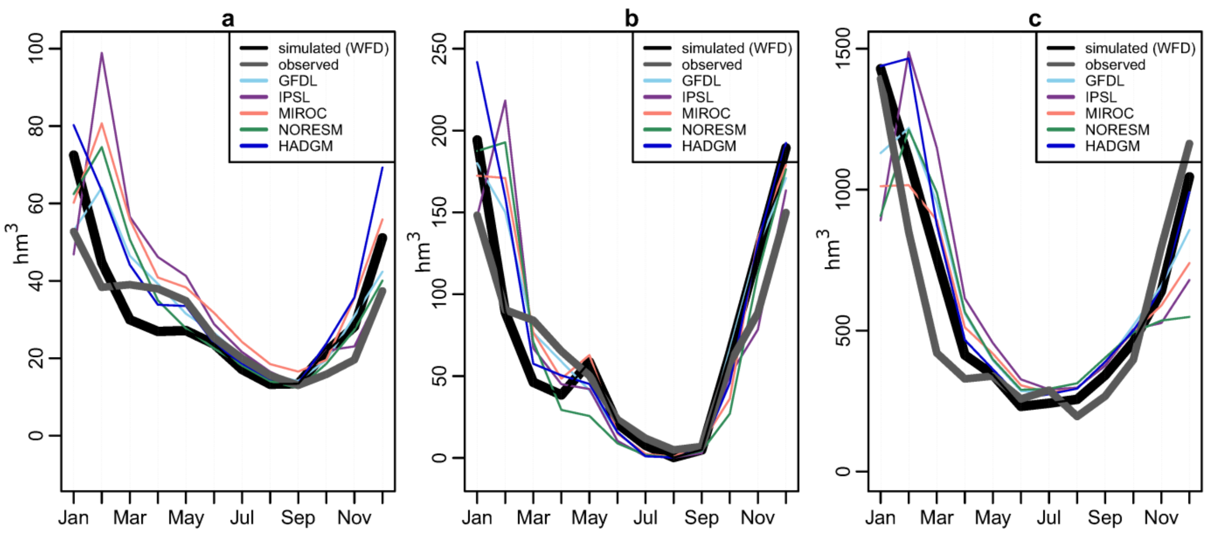

Figure 3.4 Seasonal dynamics of the inflows into the reservoirs Buendía (a), Gabriel y Galan (b) and Fratel (c) over period 1987-1999 observed, simulated with WATCH and simulated with the reference climate dataset obtained from the climate projections.

3.5.4 Projected changes in the discharge of the Tagus River basin at the Almourol gauge

Changes in river discharge, inflow into the reservoirs and in the produced hydropower were estimated as the relative difference between the long-term average monthly values between the future and reference periods, expressed in percentage.

As presented in Figure 3.5 the discharge of the Tagus River under the RCP4.5 is projected to decrease up to 30% on average until mid-century and then stabilize at this rate until the end of the century. Under the RCP8.5 scenario, river discharge is expected to decrease on average by 30% until mid-century and reaching up to 60% decrease by the end of this century. The spread of the models indicates lower uncertainty for the far future period for the extreme scenario and for the near future period for the moderate scenario.

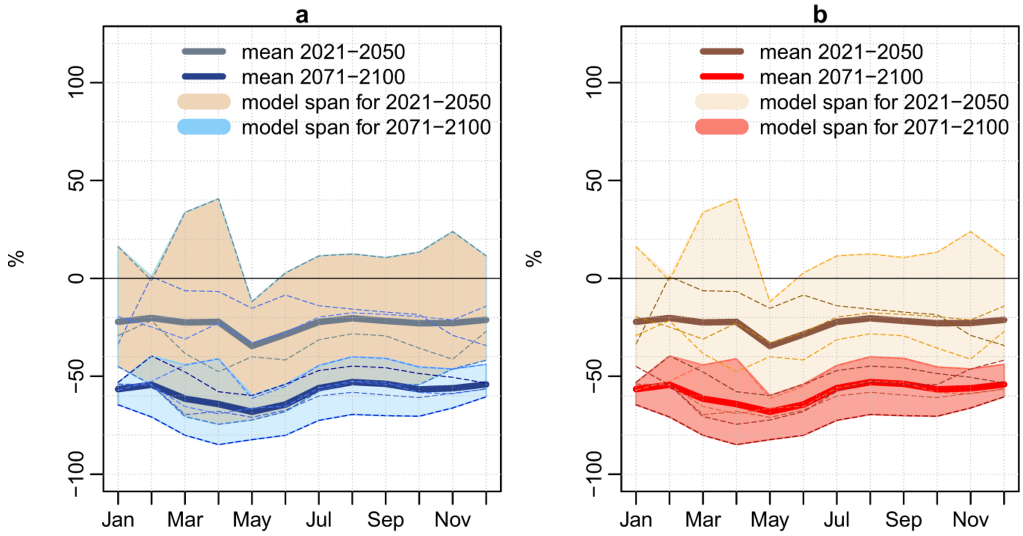

Figure 3.5 Alterations of the discharge of Tagus River basin at the Almourol gauge for two global warming scenarios RCP4.5 (a) and RCP8.5 (b), five GCM's and two future periods, as percentage of change relative to the reference period (1971-2000)

3.5.5 Climate impact on inflows into reservoirs and hydropower production

Figure 3.6 presents the percentage of change in hydropower production relative to the reference period for the three reservoirs for both climate scenarios and two future periods. As a result of decreasing inflows, the hydropower production in all three reservoirs is likely to decrease under both warming scenarios in both future periods.

This signal is very distinct for all reservoirs under RCP4.5 in the near and the far future. An exception is the reservoir Gabriel y Galan, where some models project an increasing production between January and April in the far future. Average annual reduction of hydropower production in both future periods is between -10% and -50%. Indicated by the larger model spread, the uncertainties for this climate projection are larger in the far than in the near future.

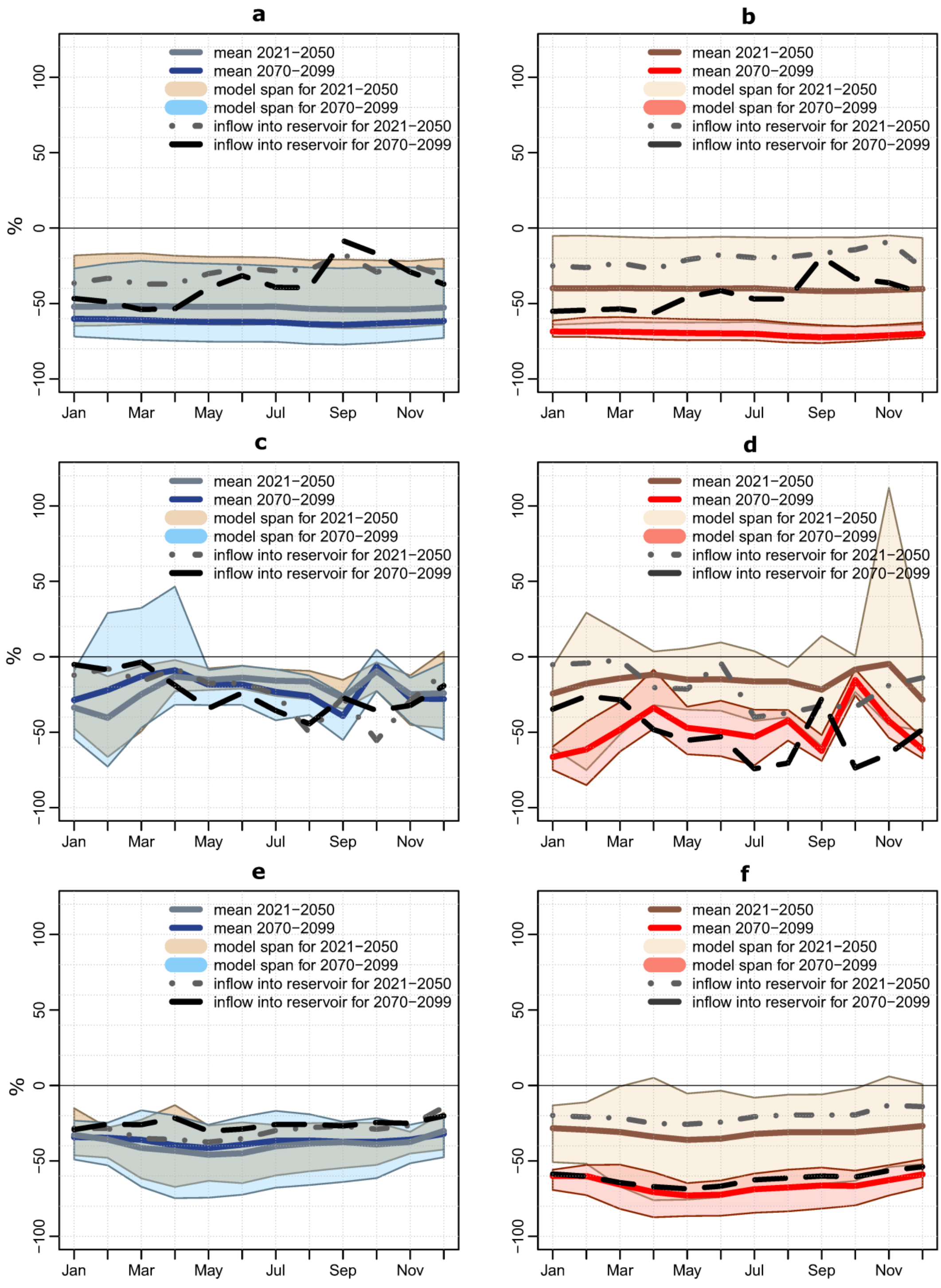

Figure 3.6 Deviations in hydropower produced in the near and far future, under RCP4.5 (left) and RCP8.5 (right) warming scenario against the mean deviation in the inflow into reservoirs: Buendía (a, b); Gabriel y Galan (c, d); Fratel (e, f)

Under the RCP8.5 projection, hydropower production is projected to decrease for all three reservoirs in the far future from -40% to -60%. The largest uncertainties are projected under RCP8.5 in the near future period, where the model spread covers a range from slightly increasing to largely decreasing hydropower production. These patterns are similar to the results shown in Figure 3.5, where two out of five GCMs project increasing average annual precipitation. However, the multi-model mean of all simulations in all periods and scenarios is showing a decreasing trend in hydropower production.

The changes in inflows and hydropower production of the Fratel reservoir (Figure 3.6 e, f) show similar dynamics. On the contrary, in the case of the Gabriel y Galan and Buendía reservoirs the mean changes in inflow have different dynamics compared to the projected changes in hydropower production. Owing to their larger storage capacity, these reservoirs have a larger potential to buffer, at least to some extent, the effects of the projected climate change by adapting the management strategy to new inflow patterns.

The projected changes in the inflows into the Gabriel y Galan reservoir showed less agreement then in the case of the Buendía or Fratel reservoirs, where a decrease in discharge was projected throughout the year for both future periods under RCP4.5 and far future period under RCP8.5. At the same time the model spread indicates a high degree of uncertainty in the inflow change, especially in the winter months for both scenarios (see Figure A8 in Appendix I), therefore results for this reservoir can be seen as uncertain.

3.6 Discussion and conclusion

The SWIM model is able to capture the discharge dynamics of the Tagus River at the monthly time step with and without reservoir module. Yet the effects of reservoir management on the seasonal discharge dynamics, in particular the decrease in winter and the increase in summer, are much better represented when the reservoir module is included. However, the “good” discharge simulations without reservoir module were achieved by increasing the time water is stored in the soil, i.e. increasing the groundwater residence time, thereby losing the physical basis of the simulation. The latter is a prerequisite for reliable simulating of the hydrological effects of changing climate or land use. The positive bias in RVE between the calibration and validation periods, in case of Gabriel y Galan and Fratel reservoirs can be explained by developments of water withdrawals for irrigation upstream.

The SWIM model including the reservoir module used in this study was able to adequately represent the past seasonal dynamics of the Tagus River at the outlet and at the inlets of the reservoirs using GCM climate data of the reference period.

The results of this study show that the discharges of the Tagus River at gauge Almourol are decreasing under both RCPs in both future periods. In RCP4.5, the average decrease in the discharge of the model ensemble in both future periods is about 30%. Same changes in discharge were simulated under the RCP8.5 scenario in the near future period. By the end of the century the decrease in discharge is expected to reach approximately 60%. In compliance with the decrease of discharges at the outlet as well as at the inlets of the reservoirs, hydropower production at all reservoirs is projected to decrease in the near and far future under both moderate and extreme climate scenarios. The findings of this study are in line with the results presented by CEDEX [122], Kilsby et al. [57] and Diogo et al. [121].

As shown by Gonzalez-Hidalgo et al. [107] and Guerreiro et al. [56], seasonal preciptiation patterns have slightly shifted in the past. Precipitation increased in autumn (October) but decreased in winter, spring, and summer. The deviation in discharge at the outlet shows the lowest decrease in autumn under both RCPs for the near future period, where some GCMs project even an increase in precipitation for this period. However, the multi-model means show decreasing discharges in all months in the Tagus River basin for both future periods and both RCPs. The largest decrease is simulated in the late spring. The Gabriel y Galan reservoir is subject to the highest uncertainties, where opposing trends of GCMs in the winter and late autumn are pronounced.

The vulnerability of hydropower production to climate change depends on the type of plant. Run-of-the-river plants usually have, due to smaller storage volumes, a lower adaptive capacity compared to that of large reservoirs [96]. The results support this statement, showing that under climate change, the Fratel reservoir would have lower adaptive capacity for projected changes because hydropower production depends directly on the inflow into the reservoir. On the contrary the reservoir Buendía with a comparably large storage volume might have a higher adaptive capacity to alleviate at least some impacts of climate change, as hydropower production levels and reservoir inflows have different dynamics, allowing for options to adapt the plant’s management. However, it is important to note that the results of this study show that the inflows into the larger storages like Buendía and Gabriel y Galan are decreasing throughout the whole year making them also highly vulnerable to the projected changes and indicating that their adaptive capacity will be also very limited, however still higher than in the case of Fratel reservoir. The current management strategy of flow regulation in the Tagus River basin prescribes storing of water in winter and releasing in summer, to cope with strong annual variability of discharge. Therefore, potential changes in discharge in winter will have higher absolute values than those in summer, challenging the management and adaptive strategies even more.

According to the simulation results, all three reservoirs have fairly different responses to climate change. As Schaefli [96] discussed, the assessment of hydropower production under climate change has to be performed together with the assessment of potential developments in water demands of other water users upstream, as those can outweigh the potential climate impacts. Lorenzo-Lacruz et al. [109] suggest that in general there are three main factors conditioning flow trends on the Iberian Peninsula: land use change, climate variability and water management. The extensive network of irrigation channels in the Tagus River basin was not considered in this study. This is clearly a limitation of this study and it needs to be investigated in further studies. In the case of the Fratel reservoir, inclusion of the upstream water withdrawals would not reverse but amplify the hydrological impacts of climate change. It is also the case of the Gabriel y Galan reservoir where inflows are affected by irrigation channels upstream. In the case of the Buendía reservoir, inflows into the reservoir can be considered as "natural", as no significant irrigation and agricultural activities are situated upstream. However, the water transfer to the Segura River basin can impose a demand on the management of the reservoir, forcing it to discharge more water in the summer and autumn months, limiting its adaptation capacity. Following the same logic, albeit Fratel reservoir has lower ability to adapt to climate change, its adaptation capacity might be "hidden" in the alteration of management strategies of the large storages upstream, like the reservoirs Cedillo or Alcantara dams, or potential decrease in water withdrawals and transfers upstream.

Chapter 4

4 Harmonizing human-hydrological system under climate change: a scenario-based approach for the case of the headwaters of the Tagus River

This chapter is a postprint version and was already published in:

[86] Lobanova, A.; Liersch, S.; Tàbara, J. D.; Koch, H.; Hattermann, F. F.; Krysanova, V. Harmonizing human-hydrological system under climate change : A scenario-based approach for the case of the headwaters of the Tagus River. *J. Hydrol.* **2017**, *548*, 436–447 https://doi.org/10.1016/j.jhydrol.2017.03.015 © 2017 Elsevier

4.1 Abstract

Conventional water management strategies, that serve solely socio-economic demands and neglect changing natural conditions of the river basins, face significant challenges in governing complex human-hydrological systems, especially in the areas with constrained water availability. This study assesses the possibility to harmonize the inter-sectoral water allocation scheme within a highly altered human-hydrological system under reduction in water availability, triggered by projected climate change applying scenario-based approach. The Tagus River basin headwaters, with significant disproportion in the water resources allocation between the environmental and socio-economic targets were taken as a perfect example of such system out of balance. In this study three different water allocation strategies for this region, including two conventional schemes and one imposing shift to sustainable water management and environmental restoration of the river were proposed. This study combines in one integrated modelling framework the eco-hydrological process-based Soil and Water Integrated Model (SWIM), coupled with the conceptual reservoir and water allocation modules driven by latest bias-corrected climate

projections for the region and investigate possible water allocation scenarios in the region under constrained water availability in the future. The results show that the socio-economic demands have to be re-considered and lowered under any water allocation strategy, as the climate impacts may significantly reduce water availability in the future. Further, it was shown that a shift to sustainable water management strategy and river restoration is possible even under reduced water availability. Finally, the results suggest that the adaptation of complex human-hydrological systems to climate change and a shift to a more sustainable water management are likely to be parts of one joint strategy to cope with climate change impacts.

4.2 Introduction

During the visit of the EU commissioners to the headwaters of the Tagus River basin on the 9th of February 2016 the local stakeholders described the river to them as "practically dead" [141]. Here, nearly all available water resources are allocated to the economic needs of the Southeast of Spain through the famous Tagus-Segura Transfer, leaving the Upper Tagus River itself (characterized by a high seasonal of flows in natural conditions) with the constant minimal flow throughout the year. This water management strategy has launched the so-called "la guerra del agua" or "war over water" between the local stakeholders, worried about the environmental state of the river, and the beneficiaries of the controversial Tagus Segura Water transfer, interested mainly in economic profits. The EU commissioners expressed their high concerns regarding the state of the Tagus river, criticizing Spanish water management course, and underlined the necessity of a shift to the Integrated River Basin Management, to comply with the Water Framework Directive (WFD) requirements [142].

There is a historic tradition of water management practices in Spain due to endemic asymmetry between water demands and water availability across the country, characterised by strong seasonality and inter-annual variability. Over the whole 20th century the water management paradigm of the Spanish government was focused on satisfying water demands of key economic sectors and was largely ignoring the environmental concerns [143]. Up until now, the general management strategy of Spanish rivers clearly prioritizes the short-term economic interests [144] instead of having a long-term view of the economic, social, and environmental benefits of adopting a more integrated sustainable water management approach, as required by the WFD. Even though the allocation of the environmental flows was mentioned as the most important measure for river restoration in the Spanish National Strategy of River

Restoration, which emerged after the WFD launch [145], there is a large social and cultural pressure against it. Assigning scarce and highly profitable water resources to the environment is perceived by the stakeholders as a misuse of a valuable resource [144].

Nowadays many rivers, like the Tagus River, cannot be considered as solely natural systems anymore, but as the coupled human-hydrological systems due to significant alterations in the hydrological dynamics imposed by humans. Such systems are characterized by a high complexity and reciprocal feedbacks of their components [146]. Often, when management strategies of these systems are serving solely economic and social needs, as in the case of the Tagus River, the sustainable limits of the natural hydrological system have been exceeded [147]. This increases their vulnerability to the projected changes in climate, if a decrease in river discharge is projected and escalates the probability of the potential collapse of a hydrological system. This, in turn, would lead to strong adverse effects on humans [147], and therefore the resilient functioning of the human-hydrological systems has to be ensured.

To tackle such problems, the Integrated Water Resources Management (IWRM) approach has been proposed as a way to harmonize multiple social, economic and ecologic goals while accounting for the risks related to climate change [4,148]. The IWRM approach, among other aspects, implies sustainable re-allocation of the water resources among water users and harmonization of the water demands of the system, including the allocation of water resources to the environment [149]. The IWRM approach is also aligned with the Sustainable Development Goals (SDGs) spearheaded by the United Nations, in particular the goal on 'Life on Land' designed to protect, restore and promote sustainable use of terrestrial ecosystems, and stop land degradation and biodiversity loss [150].

The issues, associated with water allocation and re-allocation for sustainability, were thoroughly discussed by Marson and Cai [149]. The process is associated with many challenges and requires integrated and interdisciplinary approaches [151] and it has to account for long-term hydro-climatic variations. While there is a large body of research on optimization of water allocation among users for maximization of the economic profits and benefits, the issue of water allocation to the nature still lacks enough attention. Among the recent assessments considering allocation of water to the environment are e.g. a study conducted by Cai and Rosengrant [152], who assessed the water allocation scenarios for the Yellow River in China, and a study by Suen and Eheart

[153], who performed an assessment of the reservoir management strategies to meet the environmental and human demands in the Dahan River, in Taiwan. In Spain, Varela-Ortega [154] performed a study of policy implication on the trade-offs between the water allocation to agriculture and environment. She engaged a hydro-economic and hydrological model to study policies for an aquifer in the Guadiana River Basin.

In Spain, where the regulation capacity of the rivers is almost exhausted, and many rivers can be classified as the “closed” type [151] as practically all available water resources are already allocated, the expected changes in climate and associated decrease in water availability will make the management of such systems even more challenging [155]. The assessment of climate change impacts on water availability in Iberia was performed on the scale of the Iberian Peninsula, as well as for single river basins, or their parts (e.g. Kilsby et al. [57], Moran-Tajeda et al. [120], Lopez-Moreno et al. [156], Guerreiro et al. [56], Gonzales-Zeas et al. [155], Lobanova et al. [76]). All studies agreed on decreasing trends in precipitation and reduced water availability in the Iberian Rivers, especially under high-end scenarios. These trends can be considered to be robust as the studies conducted employed different methodologies, hydrological models and global warming scenarios.

This study aims to investigate the opportunity to reallocate the water resources within a highly modified human-hydrological system, in order to ensure environmental restoration of the hydrological system while still supporting the socio-economic activities in the face of moderate and high-end climate change. Taking the headwaters of the Tagus River Basin as a critical example representative of a highly altered human-hydrological system, the possibilities to impose a more sustainable operation of the reservoirs maintaining environmental flows in the river while still supporting the operation of the Tagus Segura water transfer employing scenario-based approach were explored. The Soil and Water Integrated Model (SWIM) [41], coupled with water allocation and reservoirs modules was applied to simulate the of water allocation scenarios within the coupled human-hydrological system of the Tagus River headwaters in one integrated framework. This study employed the latest climate change scenarios to assess the deviation in the water inflow, volumes of the reservoirs and water supplied to the Southeast Spain triggered by climate change under different management strategies. While current study accounts for the influence of the humans on the hydrology and environmental state of the Tagus River it should not be confused with the coupled human-nature system study, which can account for two feedback loop to represent the dynamics of the system: influence of the humans on hydrology and hydrology influences the humans, while scenario-based approach applied in these paper only accounts for the influence of the humans on hydrology.

In this study it was shown that current conditional management strategy of the Tagus headwaters, based on assumptions of the past has not only exceeded the limits of the hydrological system, but is also unsustainable in the face of moderate and high-end climate change. The results of this study point that a shift to the IRBM in the highly-modified human-hydrological systems is possible even under reduced water availability, triggered by climate change.

4.3 **Case study**

The Tagus River basin is one of the largest and the most important rivers in the Iberian Peninsula (IP). With the catchment area covering approximately 80,000 km^2 and average annual discharge of 500 m^3/s at the outlet, the Tagus River is an important strategic water resource for Portugal and Spain. Approximately 15% of Spanish and 30% of Portuguese population depend on water resources provided by the Tagus River basin, which are used for irrigation, domestic water supply and hydropower production. Due to that and significant inter-annual variability of flows, with the high flows in winter and low flows in summer, the Tagus River basin is also one of the most regulated rivers in Europe. An extensive network of water abstraction channels and reservoirs emerged in the basin since the 1960s, ensuring the continuous and stable water supply for agricultural, hydropower and urban water demands throughout a year.

During the Franco times an idea of transferring water from the Tagus river to the southeast of Spain has emerged as a measure to overcome water deficit hindering the agricultural production and, hence, the economic development in the Murcia, Alicante and Almeria regions. The Tagus-Segura water transfer (TST) was organized at the outlet of two large reservoirs Buendía and Entrepeñas (in the following *B-E reservoirs*) (see Figure 4.1a). Since the very beginning of the TST existence the societal reaction to it was increasingly controversial. Even if the amount of water resources available on the scale of the whole Tagus River basin seems to be significant, in the Tagus headwaters nearly all water resources available are now withdrawn for socio-economic purposes, supplying the Tagus riparian ecosystem with a constant minimum flow which was defined in the first iteration cycle of the WFD implementation.

The environmental flows in the Tagus River were calculated with the RHYHABSIM model [157], and prescribe constant flow of 6 m^3/s at the Aranjuez gauge (largest city downstream of the B-E reservoirs and the TST point of withdrawal, see Figure 4.1) ignoring the natural hydrological patterns of the river. Despite the demands of local stakeholders for more water in the reach (e.g. at least 11 m^3/s at Aranjuez [158]), in the new River Basin Management Plan for the period 2016-2021 emerged in December 2015 the environmental flow rate remained the same as before [103].

On the one hand, it is obvious that the operation of entire human-hydrological system in the headwaters of the Tagus River with the only aim to satisfy the anthropogenic demands puts the aim of the Good Ecological Potential (GEP) achievement in the Tagus headwaters out of the question, failing the WFD goals. It will also hinder the adaptation capacity of the system in view of expected reduction in water resources availability due to climate change. But, on the other hand, shutting down the water transfer and cutting the water supply to the anthropogenic needs in favour of environmental state of the Tagus River would result in an economic downturn for the regions and large societal stress, as thousands of people there would become unemployed. Therefore, such system has to be brought into balance regarding both the societal needs and the environmental constraints.

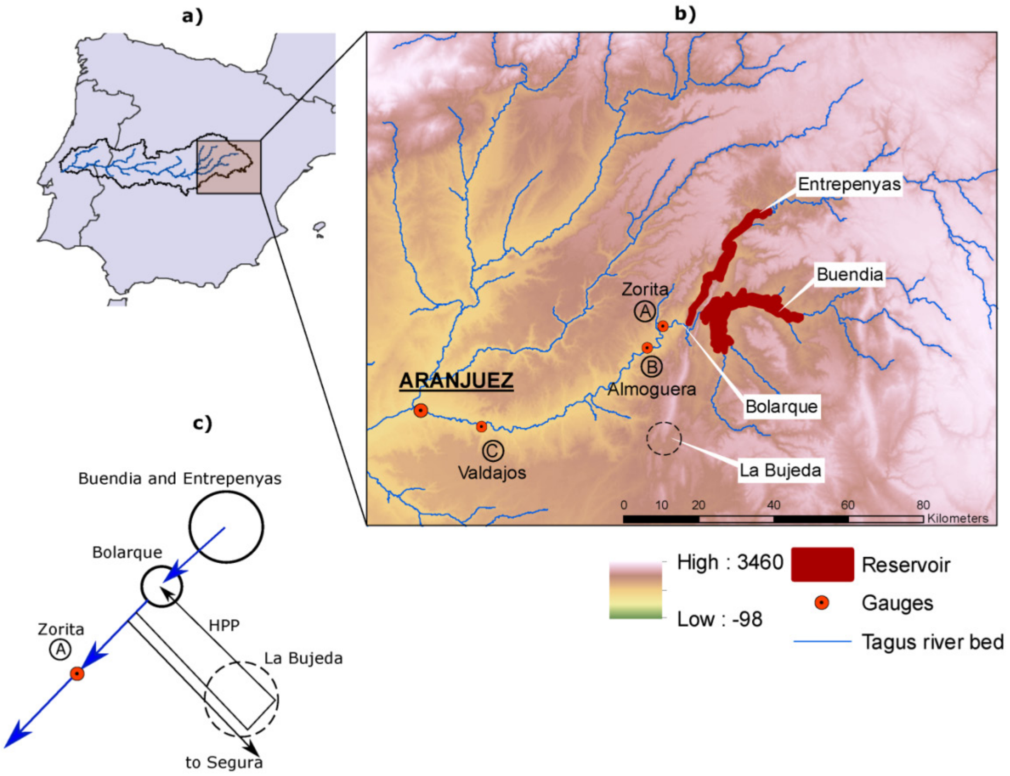

Figure 4.1 Situation map of the Tagus River basin in the Iberian Peninsula (a), the upper Tagus and the Buendía - Entrepeñas system (b), and the water management scheme analysed in this study (c)

4.3.1 The upper Tagus and Buendía-Entrepeñas System

The Buendía and Entrepeñas reservoirs are large storages with active volumes of 1,638 hm^3 and 803 hm^3, correspondingly, constructed in order to provide flood protection and satisfy basin's own needs for water resources, e.g. for irrigation and hydropower production, and later also demands of the southern-eastern river basins in Spain as well [159]. Both B-E reservoirs are discharging into the reservoir Bolarque, with a small storage capacity of 30 hm^3 which is being used solely for hydropower production. The Bolarque reservoir consists of two hydropower stations: one of the reservoir type (Bolarque I) and second of the pumped storage type (Bolarque II). In the latter case, water is being withdrawn from the Bolarque reservoir and pumped to the La Bujeda reservoir, which is situated 13 km to the south and 298 meter higher, from where water is discharged back to the Bolarque reservoir to produce electricity or is routed to the aqueduct to be delivered to the Segura River basin. Figure 1 presents the location of the

B-E system and a schematic representation of water flows between the La Bujeda and Bolarque reservoirs.

4.3.2 Tagus – Segura Water Transfer

The project of transferring water from the Tagus River to the southeast of Spain promised to boost the agricultural production and economic growth of the eastern coastal provinces. The aqueduct pipeline of 286 km towards the Talave reservoir in the Segura River basin headwaters [160] came into operation in 1979. In the first phase the maximum volume of water allowed to be transferred was planned to be 600 hm^3/year, and in the second phase, which in fact was never realized, up to 1,000 hm^3/year. The water volume to be transferred to the Segura catchment is determined based on the stored volume of water in the B-E reservoirs at the beginning of each month. The latest TST operation rule was introduced in September 2014 by Spanish Ministry of Agriculture and Environment [161] and is summarized in Part A9 of Appendix I.

The decline of river flows in the headwaters in Spain since 1980ies, which has also affected the volumes of the B-E reservoirs, has put significant limits on water resources availability in the upper Tagus (the so-called "eighties" effect), in comparison to the period before 1970 based on which the water volumes to be transferred were estimated. The inflows into the B-E system during 1981-2005 in comparison to 1958-1980 nearly halved, from about 1,500 hm^3 per year to only 770 hm^3 [110–113]. In fact, over the whole 35 years of the TST existence, the average yearly volume of water transferred was about 350 hm^3/year, and reached the planned value of 600 hm^3/year only during a few years.

In the recipient basin, the Segura, the ratio between water demand and renewable water resources is extreme: it varies from 2.1 to 2.3 times, resulting from about 1,700 hm3/year demand and only 823 hm3/year supply, on average in the period 2001-2015 [162]. The 85% of the total withdrawals are imposed by irrigated agriculture. The agricultural production in the Segura catchment are highly profitable as the region has beneficial temperatures throughout the year, productive land and traditional focus on irrigated agriculture, hence, skilled workers and the latest technologies available. This resulted in the ability of the region to produce crops at very competitive prices [110,112] . The agricultural sector, which depends on the TST, generates 1,268 € million in the Segura region, and secures 60,000 job places, what makes up around 40% of the entire agrarian employment in the region [163].

4.3.3 Analysis of water flows downstream of the Buendía-Entrepeñas System

An analysis of water flows downstream the B-E system and the TST over the last 100 years was carried out in order to identify the natural dynamics, degree of alteration of the river and estimate the environmental flows range for the Upper Tagus system. The sources of data are summarized in Table A10 of Appendix I. Location of the gauges is presented in Figure 1b. Between the outlet of the B-E system and the gauge in the Aranjuez four large irrigation channels are situated, from which water is withdrawn to irrigate fields.

Figure 4.2 presents the long-term average seasonal dynamics of discharge in different periods, obtained from the gauging stations presented in Figure 4.1b and described in Table A10 of Appendix I. The natural water cycle of the upper Tagus is characterized by a strong natural variability, as shown in Figure 4.2, with high discharges in February and March followed by low flow conditions, which persist throughout summer and early autumn. After the construction of the B-E reservoirs the strong intra-annual variability was completely eliminated, resulting in practically constant flow conditions throughout the year. After the introduction of the TST in 1979, the flow remained nearly constant over the year, but the rate of flow decreased dramatically, dropping from 37-40 m^3/s to 12 m^3/s, on average. Surprisingly, when the WFD came into play, the river flow has decreased even more, as indicated by the mean monthly discharge over the years 2001-2014. Though this period was characterized by strong drought conditions, the priority was still given to the economic targets, rather than to environmental ones, as the demands in the Mediterranean basins were growing. This phenomena was described by Lorenzo-Lacruz et al. [164].

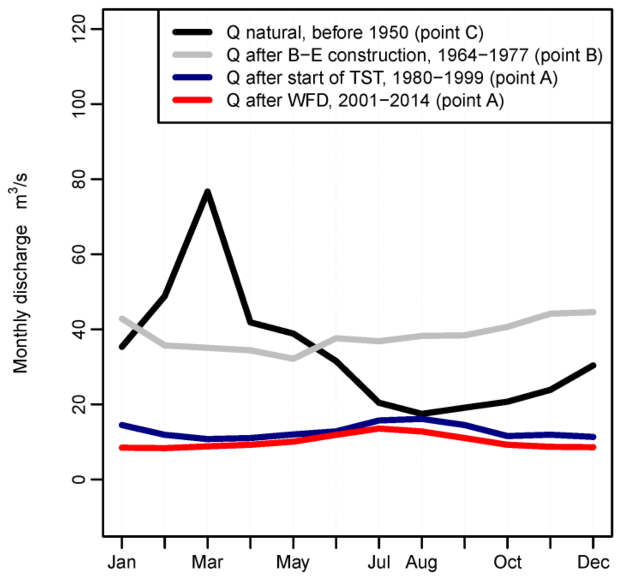

Figure 4.2 Long-term average seasonal dynamics of flows downstream of the B-E reservoirs and the TST before regulation of the river (natural conditions), after construction of the B-E reservoirs and after the start of the TST operation. Different gauges are referred as A, B and C are indicated in Figure 4.1

4.4 **Methods and data**

To explore of the water allocation scenarios within the coupled human-hydrological system of the Upper Tagus and its implications regarding water volumes delivered to the Segura River basin under different management strategies and projected changes in climatic conditions, the eco-hydrological process-based semi-distributed model SWIM coupled with the reservoir and water allocation modules was employed. Initially, the model was set up, calibrated and validated for the entire Tagus River basin, including sixteen largest reservoirs (see Lobanova et al. [76]), whereas the current study is focused only on the headwaters of the Tagus river.

4.4.1 SWIM model

The Soil and Water Integrated Model (SWIM) is a catchment scale model, which allows simulating river flow, nutrients as well as sediment discharge on a daily time step. Models of the eco-hydrological type typically consist of several sub-modules, which represent runoff, nutrient cycling and crop/vegetation growth processes. The SWIM model consists of the sub-modules, representing processes taking place in the pedosphere, hydrosphere as well as vegetation growth with similar levels of complexity. SWIM has three levels of spatial disaggregation: basin to subbasins, based on the Digital Elevation Model, and subbasin to Hydrological Response Units (HRUs), which are formed by overlapping of the subbasin, soil and land use maps, and represent areas within a subbasin with a unique combination of the land use and soil types. The water and nutrient flows are calculated on the level of HRUs, also called hydrotopes, and then routed through the reaches using the Muskingum method. Detailed information about the model components can be found in Krysanova et al. [41]. The SWIM model is undergoing further development, and in recent years it has been extended with a number of sub-modules: an extended snow module [75], irrigation module [84] dynamic land use module [82], reservoir module [85], and water allocation module.

The SWIM model has more than 25 years history of applications to medium and large-scale basins in different parts of the world (e.g. in Europe: Hesse et al.[165], Hattermann et al. [5,80], Stagl et al. [166], Huang et al.[167]; in Africa: Aich et al.[73,82], Liersch et al. [79]; in Asia: Wortmann [83]) to address different issues, like impacts of land-use change on hydrology, impacts of climate change on discharge and hydrological extremes, water quality, reservoirs performance and hydropower potential. The paper of Krysanova et al.[43] provides an extensive overview on the calibration and validation of SWIM, as well as an overview of the studies performed.

4.4.2 The reservoir module

The reservoir processes in SWIM are represented by a reservoir module, described in Koch et al. [85]. It is a conceptual representation of the storage-release processes based on three management options, to which the reservoirs are assigned according to their operation type:

i) option one: objective of the minimum discharge downstream with the consideration of minimum and maximum volumes of the given reservoir at a given month;

ii) option two: daily release based on the firmly established hydropower production requirements;

iii) option three: daily release based on the water level of the reservoir.

The reservoir is integrated into the model as an additional subbasin, and during simulation water is routed to the reservoir, and the inflow, volumes and discharge are calculated daily, taking into account seepage and evaporation from the reservoir surface.

4.4.3 The water allocation module

The water allocation module (WAM) represents the process of water allocation within or outside the basin for the transfer or irrigation purposes. The WAM is able to represent: i) water transfer from a subbasin to another subbasin (e.g. to irrigation channels or from reservoir to reservoir); ii) water transfer from a subbasin to another basin (e.g. in this case: water transfer to the Segura River basin), and iii) water withdrawals for irrigation, when transferred water is assigned as an additional precipitation in the recipient subbasin. The WAM allows assigning minimum flow requirements at the location of withdrawal, and takes the efficiency or losses of the water transfer into account. The WAM allows withdrawing required by the water user amount of water, if the assigned minimum flow conditions in the reach are secured.

4.4.4 Data sources

The datasets used to set up the SWIM model for the entire Tagus River basin are described in the A11 part of Appendix I and in Lobanova et al. [76]. For this study, it was necessary to re-calibrate the model using the WATCH Era Interim dataset [39] as climate input, based on precipitation data obtained from the GPCC dataset. This is because the climatic projections used in this study were provided by the IMPRESSIONS "Impacts and Risks from High-End Scenarios: Strategies for Innovative solutions" project (FP7) (www.impressions-project.eu) and were bias-corrected to this dataset.

4.4.5 Calibration and validation process

The SWIM model was set up for the entire Tagus River basin, and calibrated and validated over the period 1986-2001 at the outlet gauge at the Almourol town. Below the information on calibration and validation of the Upper Tagus system only over the period 1990-2010 is provided.

At the first step, the water inflows into the B-E reservoirs (in hm^3/month, according to the observed data availability) were calibrated over the period 1990-2000 and validated over the period 2001-2010. It was done by adjusting nine calibration parameters: two routing coefficients, ground water delay coefficient, coefficients to correct saturated conductivity and evapotranspiration, baseflow factor, Manning coefficient and two parameters for surface runoff. Both reservoirs were assigned to management type two (see section 3.2), and the stored water volumes and the reservoir outflows were calibrated on the monthly time step, taking into account hydropower plant release capacity and adjusting the special monthly coefficients, representing percentages of the total stored water volumes that can be discharged in a given month. The reservoir characteristic curves, i.e. the dependency of the surface area, fall and water volume were obtained from the CEDEX database. The general management strategy of both reservoirs (and of many others in the Iberian Peninsula) prescribes storing water during the winter months and release of water during the summer months. The parametrization, calibration and validation procedure for the selected 16 reservoirs in the Tagus River basin are described in detail in Lobanova et al. [76].

To evaluate the model performance, the Nash-Sutcliffe Efficiency (NSE), Relative Volume Error (RVE), and R^2 coefficient were used. The RVE and NSE formulae are:

$$NSE = 1 - \frac{\sum_{t=1}^{T}(Q_{obs} - Q_{sim})^2}{\sum_{t=1}^{T}(Q_{obs} - \overline{Q_{obs}})^2}$$

$$RVE = (\frac{\overline{Q_{sim}}}{\overline{Q_{obs}}} - 1) \cdot 100$$

where Q_{obs} – observed monthly discharge, $\overline{Q_{obs}}$ – long-term mean of observed monthly discharge, Q_{sim} – simulated monthly discharge, and $\overline{Q_{sim}}$ – long-term mean of the simulated monthly discharge.

4.4.6 Conceptual representation of the Bolarque reservoir and the Tagus-Segura Transfer

The circuit of the Bolarque - La Bujeda reservoir system (the pumped hydropower plant and the TST aqueduct were represented in the model as two withdrawals within the WAM from the subbasin directly downstream of the Bolarque reservoir subbasin (see Figure 4.1c). The pumped hydropower plant was represented as the long-term average monthly withdrawals with return flow on the next day to the Bolarque reservoir, whereas the TST was represented as daily withdrawals to the outside of the basin. The long-term average monthly discharges of water returned to the pumped hydropower plant were estimated from the observed data over the period 1989-2010 as the differences between the outflows from the La Bujeda reservoir and the water amounts transferred to the TST.

Water volumes diverted to the Segura River basin were implemented as daily water withdrawals. Within the WAM, a minimum flow of 6 m^3/s downstream of the whole Upper Tagus was prescribed.

As described in section 3.3, the simulated water withdrawal is dependent on the water availability in the reach. Therefore, to verify the water balance, the water volumes withdrawn to the Segura River basin were also compared to the observed values.

For calibration of the whole system, the observed data on the outflows from the Zorita reservoir were checked as the long-term yearly average dynamics at this reservoir.

4.5 Management Strategies

This study considers three management strategies summarized in Table 4.1. They are:

- *TRAIN IN VAIN*: business-as-usual strategy, according to the rule defining the water volumes to be sent to Segura and to be sustained in the Tagus River as proposed by the Spanish Ministry of Agriculture and Environment in September 2014 (see part A9 of Appendix I);

- *SWEET DREAMS*: proposes to keep the environmental flows downstream of the B-E system according to the Range of Variability approach (RVA, [14]) estimation; and water volumes in the Tagus River beyond the ones suggested by the RVA framework are diverted to the Segura;

- *STRAWBERRY FIELDS FOREVER*: in this scenario we aim to assess if the proposed water demand by the Segura Basin Authority of 540 hm^3 (maximum) or 340 hm^3 (average) [162] per year until at least 2033 is achievable. This strategy entails also neglecting the recommendations of the WFD;

Table 4.1 Water management scenarios considered in this study

Name of Scenario	**Abbreviation**	**Min flow in the Tagus River below the B-E system**	**B-E reservoirs management**	**Max Volume to deliver to Segura**
Train in Vain (business as now)	TIV	Target discharge corresponding to the current rule specified in September 2014 (see Supplementary Material, part A1)	As defined from observations over the 2000 – 2010 period	Corresponding to the current rule specified in September 2014 (see Appendix I, part A9), depending on the volume in the B-E
Sweet Dreams (environmental flows first)	SD	According to RVA	Adjusted to resemble the natural conditions	What is left after completing the RVA target in the Tagus
Strawberry Fields Forever	SFF	What is left after completing the TST target	As defined from observations over the 2000 – 2010 period	Maximizing volumes transferred to Segura

4.6 Climate Scenarios

The climate scenarios set obtained from the IMPRESSIONS “Impacts and Risks from High-End Scenarios: Strategies for Innovative solutions” project (FP7) includes outputs from 7 GCM-RCM combinations obtained from CMIP Phase 5 and CORDEX simulation exercise [24] under RCP4.5 and RCP8.5 pathways. The selected GCM-RCM pairs portray global temperature changes from 1°C to over 4°C. They include: the high-end climate change scenarios by HadGEM2-ES, CanESM2 and IPSL-CM5A-MR (global temperature change is between 4.00 and 4.2°C) under RCP8.5, the low-end scenarios by MPI-ESM-LR and GFDL-ESM2M (global temperature increase of 1.5 and 1.1°C) under RCP4.5, and the middle-range scenarios by GFDL-ESM2M for RCP8.5 and HadGEM2-ES for RCP4.5 (both correspond to around 2.4°C degrees global warming) (all temperature increases are indicated for the end of the century).

The downscaled projections of climate scenarios were bias-corrected to the WATCH Era Interim data using the quantile mapping method [19,91]. The bias-correction period for the selected GCM-RCM pairs output embraced the period 1981-2010. Each of the climatic variables (precipitation, solar radiation, specific humidity and mean, maximum and minimum temperatures) was bias-corrected one by one independently to the WATCH data. The study of Wilcke et al. [91] shows that the quantile-mapping method allows to account for the variables interdependencies, and suggests a grid-cell by grid-cell approach to account for geographical variation. The main feature of the quantile-mapping method is the cumulative distribution function, which is constructed from the RCM calibration period and then fitted to the cumulative distribution function constructed from the observed data. The obtained function is then applied to the projection period, in this study to the period 2011-2100.

4.7 **IHA analysis**

The Indicators of Hydrological Alterations (IHA) are a set of 32 biologically relevant river flow indicators, which is used to assess the degree of modification of a river by comparing the pre and post impact periods [168]. The IHA method was widely applied to define the environmental targets to restore environmental conditions in different rivers [13,64,169–171]. As a part of the IHA methodology introduced in the paper of Richter et al. [14], the Range of Variability approach gives the preliminary minimum and maximum discharge targets for the reservoir operation, aimed in the sustaining and restoring of the aquatic ecosystem downstream based on the discharge dynamics of the pre-impact period. The study of Acreman and Ferguson [172] stresses that natural floods and natural low flow regimes are the basic elements for achieving the GEP goal, and the constant flows in the river or releases from the impoundments should be altered for resembling the natural hydrological regimes as close as possible.

4.8 **Results**

4.8.1 Calibration of the reservoirs

The observed and simulated water inflow values showed good fitting for both Buendía and Entrepeñas reservoirs. The NSE, RVE and R^2 values are presented in Table 4.2.

The volumes and outflows for the Buendía reservoir also showed good fitting results, for both calibration and validation periods. As for the Entrepeñas reservoir, where the management strategy was changed during the period 2001-2010, the parameterization which showed good fitting for the calibration period, showed very poor results for the validation period. The reservoir management was therefore corrected to fit data in the validation period, and this setting was used for the further simulations.

Therefore, in the Table 4.2 the NSE, RVE and R^2 values for the outflow during the calibration period are not presented

Table 4.2 Calibration and validation results for the Buendía and Entrepeñas reservoirs considering water inflows, volume storages and outflows

Reservoir	**Metrics**	**Inflow**		**Volume**		**Outflow**	
		Calib	**Valid**	**Calib**	**Valid**	**Calib**	**Valid**
Buendía	*NSE*	0.78	0.78	0.71	0.66	0.57	0.51
	RVE, %	-8.3	8.1	-1.6	6.4	-9.9	1.4
	R^2	0.89	0.9	0.97	0.95	0.93	0.96
Entrepeñas	*NSE*	0.87	0.8	*0.67*	0.74	*0*	0.3
	RVE, %	-7.9	3.6	*-4.3*	-3.7	*1.2*	0.3
	R^2	0.93	0.82	*0.9*	0.95	*0.3*	0.79

4.8.2 Volumes transferred to the Segura River basin via TST over calibration and validation period and inflows into the Zorita reservoir

The water volumes transferred from the Tagus River basin to the Segura River basin estimated by the WAM module showed fairly good fitting to the observed annual volumes, and resulted in an underestimation of 15% for the total volumes in the calibration period, 12% in the validation period, and R^2 of 0.91 over the period of 1990-2010. Better representation of the withdrawn volumes during the validation period can be explained by the fact that the Entrepeñas reservoir management was changed during 2001-2010, and the latest management rules were applied in the model. The systematic underestimation of the volumes of the water supplied can be due to the fact that the transfer actually is starting at the La Bujeda reservoir, which is not taken into account in this study explicitly. The discharge from the B-E reservoirs in the Tagus River could be not enough to supply the requested by Segura volume at a given day, whereas in the reality this amount is withdrawn from the stored in the La Bujeda reservoir water.

The long-term mean annual dynamics at the Zorita reservoir also showed a good fitting for the 2001-2010 period, as presented in Figure 4.3.

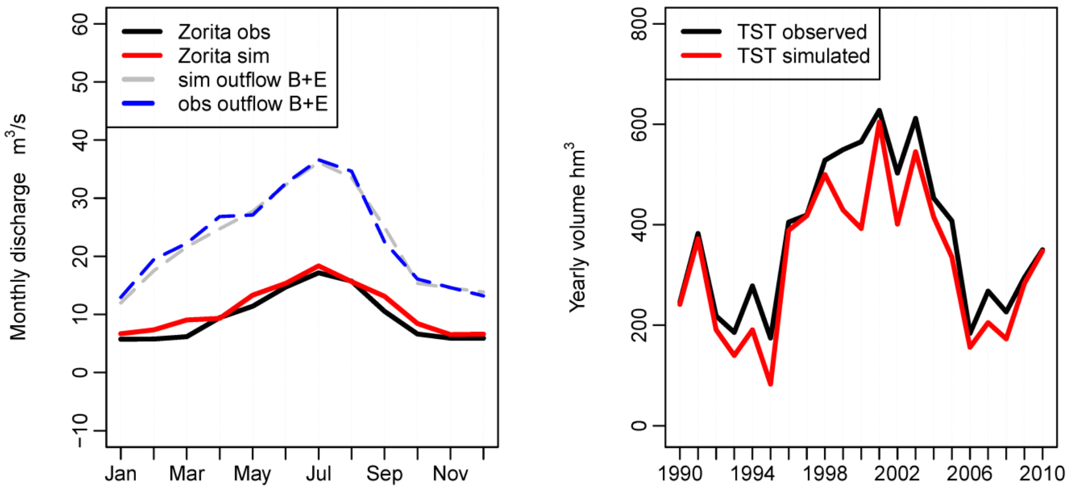

Figure 4.3 The long-term mean annual observed and simulated dynamics at the Zorita reservoir for the 2001-2010 period against the long-term mean annual dynamics of the outflows from the B-E reservoirs (left); observed and simulated with SWIM water allocation module annual water volumes delivered to Segura via the Tagus-Segura Transfer over the same period (right)

4.8.3 IHA Analysis

The assessment of the environmental flows was performed for discharges downstream of the B-E system based on data from the gauge Valdajos representing the natural regime (records before 1950), and the gauge Zorita, representing the post-impact period (records after 1980). The results of analysis are presented in Figure A12 of Appendix I. They show the estimated range of the environmental flows for the Tagus River versus the flows imposed by the latest operational rules of the TST, revealing the totally opposite dynamics of those. The environmental flows recommended by the RVA resemble the natural cycle, with the high flows in winter and low flows in summer, whereas the flows proposed by the Tagus Basin Authority CH Tajo prescribe peak in July, in order to satisfy the local agricultural demands for the irrigation and lowest flows during the winter months.

4.8.4 Climate change driven deviations in water inflow into reservoirs

Firstly, the bias-corrected climate projections were tested for their ability to represent the historical conditions adequately. Figure A13 in Appendix I shows the comparison of the observed discharge with discharges simulated by SWIM driven by the WATCH Era Interim data and by climate models outputs over 1990-2010. In general, SWIM driven by climate models was able to represent successfully the seasonal dynamics of inflows into the reservoirs. While the model fitting is good during summer months and late spring, the model spread is a bit larger during winter, early spring and late autumn months.

Figure 4.4 presents the projected changes (relative to the reference period 1981-2010) in the inflows into the both Buendía and Entrepeñas reservoirs under RCP4.5 and RCP8.5 climate scenarios, for two future time slices 2011-2040 (near future) and 2041-2070 (far future). It is evident that a substantial decrease in inflow into reservoirs is projected for far future period under RCP4.5 and for both future time slices under RCP8.5. The inflows are expected to decrease on average by up to 50% under the high-end scenario (RCP8.5) and by 20% under the RCP4.5 scenario in the far future. The model spread is related to uncertainty of climate input from GCM/RCM combinations. It indicates that under both scenarios the model agreement is lower for the far future. For the far future under RCP4.5 one model output (SWIM driven by MPI-ESM-LR) indicates a significant increase in the inflows into both reservoirs (up to 75% in December), whereas all other model outputs project decreases from -10% to up to -35%.

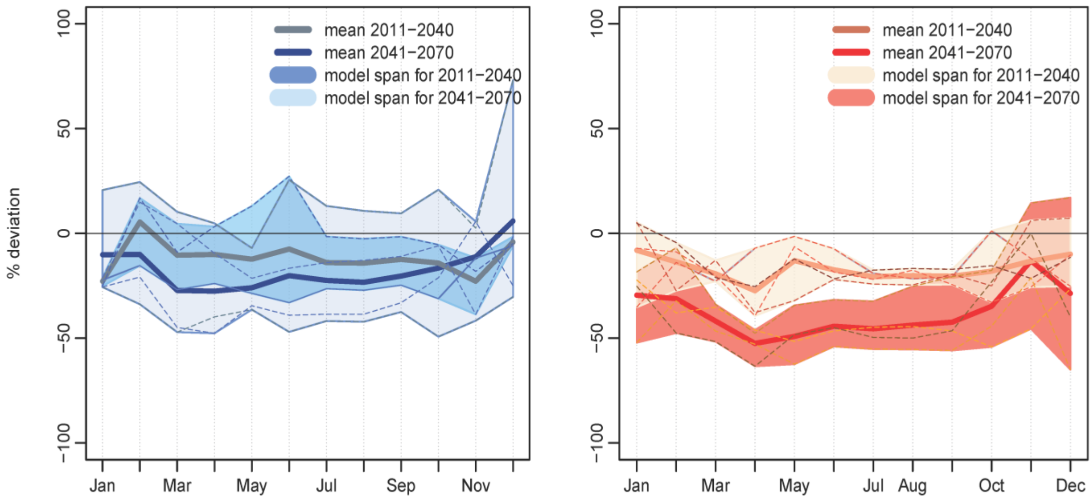

Figure 4.4 Percentage deviations in the inflows into the Buendía and Entrepeñas Reservoirs under RCP4.5 (left) and RCP8.5 (right) scenarios for the near (2011-2040) and far (2041-2070) future slices

4.8.5 Implications of the water management strategies

The following subsections are presenting simulation results for the B-E reservoir volumes, discharge in the Tagus River and yearly water volumes supplied to the Segura basins of the Upper Tagus system under water management scenarios and climate change conditions.

- Discharge downstream of the Zorita Reservoir

Discharge downstream of the Upper Tagus System was imposed by the WAM according to the water management strategies. Figure 4.5 presents the long-term average monthly discharge at the Zorita reservoir for all water management scenarios under two (moderate and high-end) climate scenarios.

Under the TIV strategy, the flow in the river follows the rule approved by Spanish Ministry of Agriculture and Environment in September 2014 (see Part A11 of Appendix I). The discharge values were assigned to be higher than those observed over 2001 -2010 period, possibly to meet increased demands for local irrigation. Under both climate projections, it will be possible to sustain the proposed discharge level in the Tagus River in the near future, given that the management of both reservoirs will remain unchanged. However, under the RCP8.5 scenario the water availability is expected to decrease stronger, and in this case the recent proposed rule may be not fulfilled anymore and discharge might approach the levels of the observed discharges over 2001-2010. The situation is similar for the green SD strategy, where the environmental flows imposed can be sustained under RCP4.5, whereas under RCP8.5 the significant decreases in water availability will put serious constraints to the fulfilment of the flow target downstream of the B-E reservoirs. It is important to mention that in case of SFF strategy in early autumn water flow can drop even below the current minimum flow requirement of 6 m^3/s at Aranjuez, putting environmental state of the river and local agricultural production under serious threat.

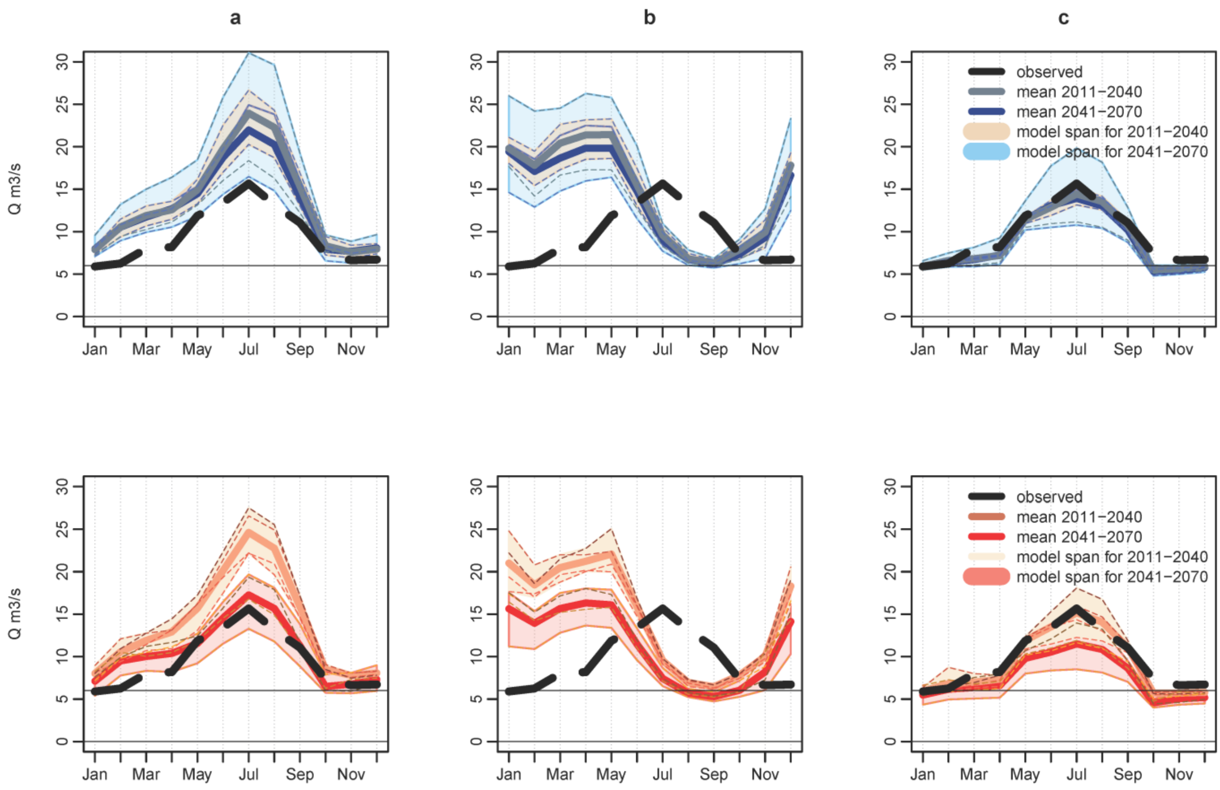

Figure 4.5 Discharge at the Zorita reservoir, the Tagus River, under different management scenarios (columns a – Train in Vain, b – Sweet Dreams, c – Strawberry fields forever) and climate projections (top – RCP4.5, bottom RCP8.5). Black dashed line is the observed over 2000-2010 discharge and the solid black line indicates the 6 m^3/s threshold

- Volume of the Buendía and Entrepeñas Reservoirs

Figure 4.6 presents the sum of the volumes of the Buendía and Entrepeñas reservoirs under two global warming scenarios and two different management strategies: as was defined over 2001-2010 years (applied in the TIV and SFF strategies), and a “green” operation, aiming to provide annual cycle which will resemble natural conditions (as used in the SD scenario).

The stored water volume in the B-E reservoirs would decrease substantially under the current management strategy combined with climate warming. A decrease of up to 25% for the far and near future under RCP4.5, and from 25% in the near future to nearly 40% in the far future under RCP8.5 with respect to the reference climate conditions is projected, as indicated by the multi-model means.

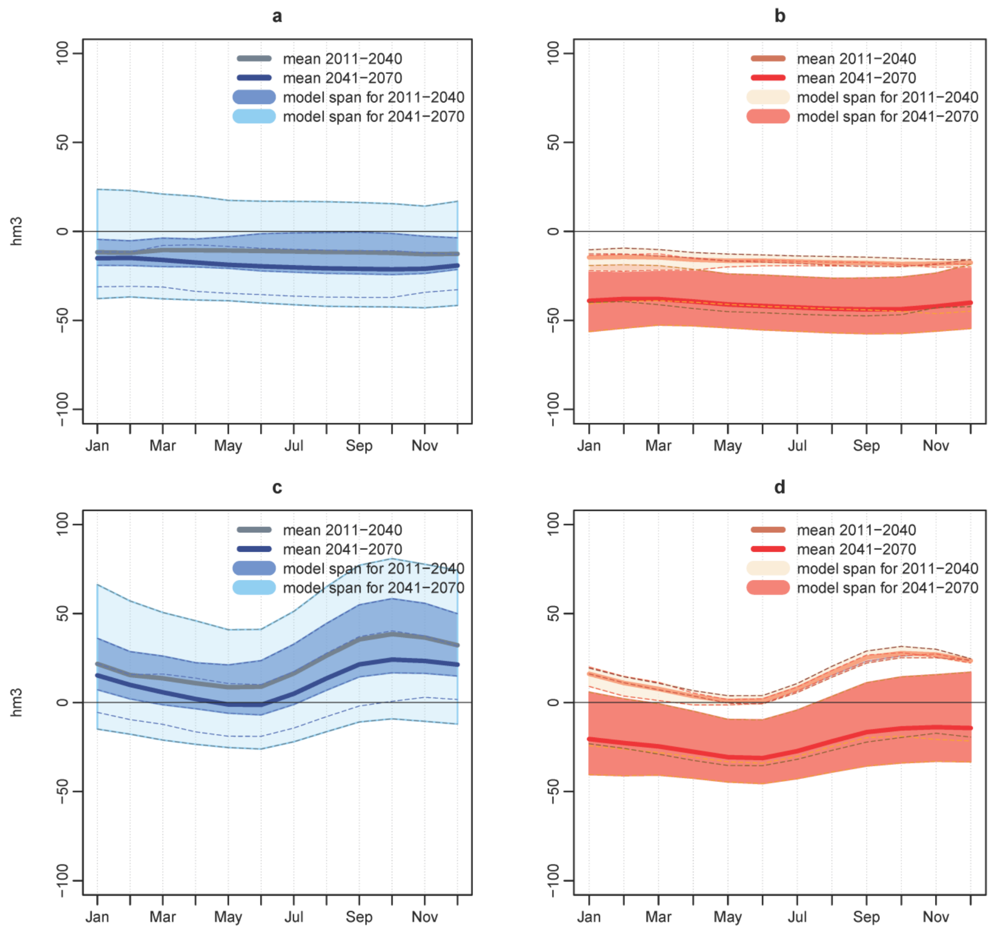

Figure 4.6 Deviations in the stored volumes of the BE reservoirs under projected climate change RCP4.5 (left) and RCP8.5 (right), under SFF and TIV management strategy (a and b) and under SD management strategy (c and d)

In terms of absolute values, the volume is reaching the threshold of 400 hm^3 throughout the year under RCP8.5 and in autumn under RCP4.5 in far future, which is defined as overall minimum by the Tagus River basin authority CH Tajo. Under these circumstances the TST is not operated.

On the contrary, the management strategy oriented towards sustaining of environmental flows in the river in the long-term would also sustain the reservoirs volume, as indicated by the multi-model mean. This strategy indicates even an increase in the stored volumes during late summer and autumn up to 30% for both future periods under RCP4.5, and for the near future under RCP8.5. However, the volumes are decreasing up to -25% with respect to the reference period in far future under RCP8.5. In terms of the absolute values, the multi-model means indicate that in case of this management strategy it is very likely to sustain the water volumes under RCP4.5 at the level which corresponds to the mean volumes observed during the 2001-2010 period, promising higher water security in the future.

- Water volumes delivered to the Segura basin

Table 4.3 shows the annual water volumes delivered to the Segura basin under moderate and high-end climate scenarios and management strategies, including multi-model mean, minimum and maximum values of the model spread for two future time slices.

Table 4.3 Annual water volumes supplied to the Segura River basin under different management and climate scenarios

RCP	**Year**	**Train in Vain**			**Sweet Dreams**			**Strawberry fields forever**		
		Min	**Mean**	Max	Min	**Mean**	Max	Min	**Mean**	Max
RCP4.5	2011-2040	150	**210**	280	107	**169**	222	214	**300**	374
	2041-2070	72	**196**	385	47	**155**	334	139	**271**	478
RCP8.5	2011-2040	175	**229**	281	117	**184**	250	255	**310**	366
	2041-2070	65	**117**	158	27	**72**	118	116	**177**	234

According to the results, the amount of water supplied to the Segura basin under the SD strategy is significantly lower than that under the TIV strategy for the far future under the RCP8.5 scenario, where the difference made up about 40% on average. For the near future under the RCP8.5 and in both future periods under RCP4.5 the difference between the two management strategies was less, reaching around 20% on average. The differences between the SFF and SD strategies were found to be larger, resulting in about 40-43% less water volumes delivered under the SD strategy in both future time slices under RCP4.5 and in near future under RCP8.5, and approximately up to 60% less under RCP8.5 in the far future. However, in the SFF strategy, the amount of water supplied to the Tagus River decreases substantially (see Fig.5), reaching the average levels observed over 2001-2010. This would result in the significantly deteriorated state of the river in the future, and, possibly lack of water resources for irrigation.

4.9 Summary and discussion

This study aimed to explore the implications of three management strategies under conditions of climate change for a harmonization of water resources allocation within the highly-modified human-hydrological system. On example of the Tagus River headwaters, the scenarios of future operation of the Buendía and Entrepeñas system, the associated evolution of the Tagus-Segura water transfer and environmental flows of the Tagus River were assessed by means of numerical modelling under projected climate change. The headwaters of the Tagus River were simulated with the eco-hydrological, process-based SWIM model coupled with the reservoir and water allocation modules, to represent the reservoir storage processes and the Tagus Segura Transfer operation.

The results of this study show that the inflow into the Buendía and Entrepeñas reservoirs is very likely to decrease in both near and far future periods under both global warming scenarios, as indicated by the multi-model means and spread in the simulation results. The projected decrease in the inflows would result in a decrease in the volume and outflows of the reservoirs, if their operation would remain unchanged (management strategies SFF and TIV). These results resemble the general trends found in other studies of climate change impacts on the hydrology, performed in this area, as discussed above.

Further, the results show that the operation of the Buendía and Entrepeñas reservoirs can be adjusted so that their coping capacity to projected climate change would increase, and at the same time the environmental flows at the Tagus River would be established and sustained under RCP4.5 in the far future and under RCP8.5 in the near future. However, in this case, the water volumes supplied to the Segura basin would substantially decrease.

On the other hand, under the current operational rule and due to reduced inflows the volumes and, sequentially, the outflows of the Buendía and Entrepeñas reservoirs would decrease dramatically under both climate scenarios in both time slices. As the water volumes to be delivered to the Segura basin depend on the volumes of the reservoirs, a decrease in the latter ones leads to a decrease in the volumes diverted to the Segura basin, falling below the 350 hm^3 target. Moreover, the results of this study show that the transferred water volumes under the TIV and SD strategies had about 20% difference under the RCP4.5 scenario. Further, even in a hypothetical situation of the total negligence of the WFD requirements, the recommendations of the European Commission and the local needs for irrigation, the target of 350 hm^3 cannot be reached in any case under current operational rule of the reservoirs and the projected future climatic conditions. Therefore the results suggest, with a high degree of certainty that in the future the beneficiaries of the Segura basin will have to count with much less water in any case and under any management scenarios.

The last three years were characterized by strong drought conditions in Spain that have led to a serious depletion of water resources stored in the reservoirs in the Segura basin. This lack of water resources has also translated into mounting conflicts and farmers' demonstrations (such as one 16/09/2016 when 500 tractors blocked the whole Murcia city), demanding higher water security.

Therefore it is increasingly urgent to think ahead about such situations and solutions to them, as they are likely to be repeated in the future more often, and may even become the new normal condition for most of Spain. So far, most responses to water problems have been dealt with conventional approaches which focus on the supply side, while at the current point a more integrated demand management approach is needed to complement it. Given that the South of Spain has already advanced some water saving technologies, like urban wastewater re-use, desalinization and modern irrigation techniques, other criteria and mechanisms, like full cost of water recovery promoted by the WFD, are not implemented yet. During the implementation of the AGUA program, which was intended to substitute the National Hydrological Plan of Spain, many desalinization plants were built in the South of Spain to ease the water stress [173]. But nowadays the plants are not working at their full capacity, as the desalinated water has a much higher price than the water supplied by conventional means (e.g. the Tagus Segura Transfer). As this situation cannot persist in the future, the challenge for the Spanish authorities is to make the desalinated water more affordable to the farmers, as new transfers (like e.g. plans on construction of the Ebro Transfer) will not solve the water scarcity problems.

Climate change impacts and its associated socio-economic pressures are very likely to cause water availability problems not only in the South and Eastern provinces of Spain but also in the donors' basins. When considering a mid and long term time perspective, the conventional paradigm of seeing water simply as a resource to harvest and re-distribute to meet economic demands, so ingrained in Spanish water management practices, is proving its very strong limitations and contradictions. This also requires not only a change in management practices but also above all a change in the way the water resources and rivers are perceived. They should be treated as adaptive, fragile and complex systems which require strong public participation and knowledge integration.

It should be emphasized that the expected impacts of climate change in the far future under RCP8.5 are very severe resulting in a strong decrease of reservoir volumes and outflows. The simulations show that not even the altered management strategy would be able to cope with such a situation.

As Watts et al. [174] argued the reconsideration of the dams operation may enhance the ecosystem restoration and help to adapt to climate change, and should be considered along with structural changes. On the other hand, Marston and Cai [149] discussed that while switching to more environmental operation of the reservoirs, the initial reservoirs functionality maybe endangered. Another issue associated with the restoration of the rivers would be the applicability of the IHA method or any other method for definition of environmental flows targets. The environmental flows establishment requires an interdisciplinary approach, involving ecological, biological and hydrological scientists accompanied by a policy-science dialogue. In the case of the Upper Tagus River, a lack of studies on the ecosystem state and water quality was found – a serious gap which has to be filled when thinking of establishing environmental flows for water ecosystem restoration.

The results of this study can be used as initial conditions for further investigations, e.g. to assess the socio-economic impacts in the Segura River basin derived from a much reduced capacity of the Tagus to provide water. Additionally, the TST is a large and expensive infrastructure that requires regular maintenance, and it is important to assess which minimum water volume transferred per year would still justify its existence.

4.10 **Conclusions**

Nowadays, when less and less rivers are characterized by the natural regimes, and human beings are essentially influencing river flows, hydrological modelling faces a challenge of integration of physical and anthropogenic processes. The methodology applied implicitly integrates hydrological and water management processes to represent a coupled human-hydrological system, and allows assessment of different water management and climate scenarios. The SWIM model coupled with the reservoir and water allocation modules proved to be a suitable tool for the modelling of such systems.

Though the anthropogenic influences are represented with intermediate complexity in SWIM, applied methodology can be used for the long-term water resources planning in such systems like the Upper Tagus and in similar regions. However, to allow for the fully integrated assessment of the socio-hydrological dynamics of this system the socio-economic modelling has to be integrated into the framework to account for mutual impacts of hydrology on humans and, in turn, humans on hydrology in this highly modified system, as the scenario-based approach applied in this paper cannot account for the reciprocal feedbacks in the system. A study of coupled human-hydrological system study type will be very beneficial for this region, as the allocation of the scarce water resources will have direct impacts on the economic and social capital of the Tagus region, as well as Segura region and can reveal important dynamics of the system.

In the case of the Tagus River basin reported results showed that even in the face of the reduced water availability the environmental flows can be established in the basin, however in this case the socio-economic demands, especially related to the water transfer scheme to Segura, should be re-considered and lowered.

The major challenge of the Spanish water management is to balance the environmental, economic and social demands [175]. The current water management structure in Spain seems to look at the past, while the constantly changing boundary conditions of the human-hydrological systems, external forces and the necessity of the implementation of the WFD call for the paradigm shift to the innovative Integrated Water Resources Management approach. There are strong cultural and economic preferences for the reducing the variability of flows in the Iberian Rivers, and it is generally hard to justify the necessity of allocation of scarce and valuable water resources to the environment. On the other hand, as Tabara and Ilhan [176] show in their paper, water use culture in Spain can also become a trigger for transition to sustainability in water sector, as was proven by cancelling the planned Ebro Transfer, and the emergence of the New Water Culture movement in Spain back in the 2000s.

The allocation of water resources to nature is a powerful instrument to enhance the water systems resilience. However, such complex systems call for interdisciplinarity and require significant policy, institutional, social and economic shifts and reconsiderations. The science-policy-stakeholders dialogue has to be established [177]. In the long-term, such integrated approaches are likely to secure win-win social, ecological and economic benefits, which cannot longer be secured following conventional strategies in water management in the face of climatic and socio-economic changes.

Chapter 5

5 Conclusions and outlook

5.1 Synthesis of the results

Two main research questions specified in Chapter 1 were driving the work for this Thesis:

- First, the impacts of climate change on water resources were assessed at three policy-relevant scales: (a) at the scale of the entire European continent considering eight representative mesoscale and large river basins in different climatic zones, then narrowing down to (b) the river basin scale, and (c) the scale of single infrastructure units, in this case - reservoirs.

- Second, the assessment of different water management scenarios was done for a highly regulated human-hydrological system under reduced water availability conditioned by the impacts of climate change, including one scenario which is sustainability-oriented and complies with the WFD requirements.

The research questions have been addressed with the application of the eco-hydrological model SWIM. The methodology and results of work were described in the three articles, which form the main body of the Thesis.

In order to perform assessment of effects of climate change on the hydrological patterns and water infrastructure functioning in the selected river basins by means of hydrological modelling, and to explore different combinations of the water management strategies the following technical tasks were fulfilled:

- Integration of water management infrastructure (reservoirs) in the model, and calibration and validation of water flows in the highly regulated rivers (Lule in Sweden and Tagus in Spain) leading to improvement of the performance of the hydrological model SWIM;
- Development of a water allocation module for the model to represent the water abstraction channels in the Tagus River basin;
- Estimation of the environmental flows for the headwaters of the Tagus River;
- Set-up, calibration and validation of the hydrological model coupled with the reservoir and water allocation modules in order to represent operation of the human-hydrological system as close to reality as possible.

The SWIM model applied in this Thesis showed its strong ability to simulate rivers different in size as well as climatic and anthropogenic conditions, what resulted in good performance criteria for all eight river basins considered. The SWIM model with the reservoir and water allocation modules showed sufficiently good simulation results also in the highly regulated river basins, such as the Tagus and Lule, though in the case of the Lule River the model had difficulties in representing some flow components due to extensive regulation. Additionally, it was possible to represent successfully good the dynamics of a nearly artificial water system – the Tagus River headwaters, where anthropogenic activities and water infrastructure define the flows of the river to a great extent, and to simulate it with a high accuracy (Chapter 2, [86]).

The results of this Thesis show that the impacts of the moderate and high-end climate change scenarios would be heterogeneous across Europe. In the Northern Europe, (e.g. for the Lule in Sweden, Northern Dvina in Russia, Tay in UK), water availability is expected to increase throughout the year under both global warming scenarios. Further, in the Eastern and Central European rivers (Rhine (Switzerland, Germany, Netherlands), Danube (Austria, Slovakia, Hungary, Croatia, Serbia, Romania, Bulgaria, Moldova and Ukraine), Teteriv (Ukraine)) discharge is expected to increase in winter and late autumn. The seasonality of river discharge in the snowmelt driven rivers in Northern Europe (N. Dvina, Lule and Emån (Sweden)) and Central Europe (Danube and Teteriv) will likely be affected under the high-end emissions scenario. The results described in this Thesis indicate a shift of the peak discharge of the above mentioned rivers to earlier dates, what is associated with an earlier melting of snow driven by an increase in temperature. For the Tagus River, representing the Southern European rivers in this study, a general decrease in discharge throughout the year is projected under the high-end emissions scenario for both mid-century and end of the century. In the case of the moderate climate change scenario, despite the fact that annual discharge is projected to decrease on average, the flows may remain within the observed ranges of the inter-annual flow variability until the mid-century, showing statistically significant decreases in the discharge only by the end of the century. Hence, it is very important to communicate to the stakeholders not only the long-term mean annual changes in discharge but also the intra-annual variability of flows in the future.

The impacts of the high-end climate change scenario are more pronounced after the mid-century compared to the impacts of the moderate climate change scenario. Namely, the trends triggered by the high emissions scenario develop until the end of the century, and under the moderate emissions scenario they level off after the mid-century. The largest differences between the impacts of the moderate and high-end climate change scenarios were found for the Northern Dvina, Lule and Tagus.

Similar to those described in this Thesis trends were reported by e.g. Papadimitrou et al. [55], Arnell and Gosling [63], Hagemann et al. [62] on the increase in discharge in the Northern Europe and decrease of discharge in the Southern Europe, and by Döll and Schmied [65] and Wanders et al. [66] on the seasonal changes in the snowmelt driven rivers. The verification of trends reported by other studies, conducted with different climate projections, scenarios and hydrological models is an important finding of this Thesis. Especially, it is the case for the previous assessments performed with the global hydrological models, whose limitations were discussed in Chapters 1 and 2. For the first time the assessment of the mean annual patterns of discharge under climate change across the European continent was done taking into account water management using a basin scale process-based model, which was thoroughly calibrated and validated for each case study in advance.

The results of this Thesis suggest that the projected changes in the hydrological regime in the Northern catchments, showing an increase in water availability in general, may create some opportunities, e.g. for hydropower production. On the other hand, in the Central European and Northern catchments the projected shifts in seasonality and discharge increase in late autumn would demand adaptation of operational rules of the water infrastructure. At the same time, the increase of discharge in autumn and winter could be potentially also a signal for the increasing probability of floods in these regions.

However, this was not investigated in depth, as it was beyond the scope of the work conducted for this Thesis, and has to be addressed in the follow-up studies. In this case, the hydrological model has to be carefully calibrated to represent the high flows and peak discharges as accurately as possible. Also the climate input data has to be checked for adequacy of the representation of extreme events in the reference period.

As shown in this Thesis and widely discussed in the literature (see also Guerreiro et al. [178], Papadimitrou et al. [55], Gosling and Arnell [3], Schewe et al. [179], Garcia – Riuz et al. [156], Estrela et al. [180]), in contrast to the Northern Europe, water managers in Southern Europe will likely have to deal with significantly decreased water availability. Water users in such basins, like the Tagus River basin considered here, with relatively scarce water resources and high natural inter- and intra-annual variability of the flow, may experience water stress already now due to extensive flow regulation and partly uncontrolled water withdrawals [181]. This situation is likely to be exacerbated in the face of future climatic changes [116], and therefore it is ultimately important to supply water managers with information on how climate change will influence water availability in such catchments, and how this in turn will impact the functioning of the water infrastructure.

Though several studies tackling the impacts of climate change in the Tagus River basin were conducted before this work, their study areas were limited either to the Spanish [122,123] or Portuguese parts of the river basin [57], or they did not account for water infrastructure, which is ultimately important for this river, in an integrated manner. The assessment presented in this Thesis is the first one covering the entire catchment area and integrating water infrastructure, including water transfers and the most important reservoirs, in one hydrological modelling framework. This allows accounting for the storage-release processes and their influence on the river discharge when assessing the climate impacts. The assessment suggests that discharge of the Tagus River is expected to decrease by more than a half by the end of the century under the high-emissions scenario. Similar results were reported by Kilsby et al. [57]: up to 50% decrease in discharge, and the Tagus Basin Authority study indicated up to 35% of discharge decrease under the high-end scenario [122,123]. The inflows into the three selected representative reservoirs located in different parts of the basin would decrease throughout the year, consequently lowering the hydropower production. The results confirm that the severity of the impacts on the hydropower production depends on the location and type of reservoir, as was discussed previously by Schaefli [96]. In particular, the reservoirs of the run-of-the-river type will have lower adaptive capacity due to their size. The decrease of discharge in winter would challenge further the current water management strategy of the Tagus River, which prescribes storage of water in the reservoirs during period of high flows in winter and discharge during summer months to meet the irrigational demands for water.

Often, in Southern European basins, like the Tagus River basin, the water resources are perceived solely as a profitable economic resource, and therefore the water management strategy prioritizes the short-term economic interests over the environmental state of the rivers [144]. For example, the current water management strategy of a highly regulated human-hydrological system in the headwaters of the Tagus River allocates nearly all water resources available to the economic needs, in particular to the water transfer to the Segura River basin, to support their highly profitable irrigational activities. This situation has aggravated the environmental and social conditions in the Tagus River headwaters and has drawn attention of the scientific community [86,110,182,183]. The challenge of water resources allocation between the competing users and environment in such catchments like the Tagus could become even more delicate issue in the future, as water availability will decrease due to climate change (as shown in Lobanova et al. [86] and discussed by Garcia – Riuz et al. [156], Varela-Ortega et al. [154,184]).

In this Thesis a thorough analysis of water allocation options was conducted, aiming to find a meaningful balance between the economic and environmental demands. The important and challenging technical task which was fulfilled for this Thesis is representation of the highly regulated human-hydrological system in the headwaters of the Tagus River, which is described in details in Chapter 4. The SWIM model was able to represent with a sufficiently high degree of accuracy the water inflows, water outflows and volumes of the reservoirs in the headwaters of the Tagus River, taking into account water volumes supplied to the Segura River basin, as well as the long-term mean annual discharge in the Tagus River downstream of the considered reservoirs.

The results of this Thesis show that despite the fact that water availability in the Tagus catchment in general, as well as at the inlets of the reservoirs in the headwaters of the river, is projected to decrease substantially, the current water management strategy can be still switched to a more environmentally-oriented one, which complies with requirements of the Water Framework Directive for imposing environmental flows in the river. However, in this case the current water resources allocation scheme has to be substantially re-considered. When shifting to the more sustainable water management strategy, the water volumes supplied to the Segura River basin would have to be strongly decreased, and the operational rules of the reservoirs would have to be adjusted to assure that reservoirs outflow would resemble the environmental flows. The latter were defined with a help of the Indicators of Hydrological Alterations (IHA) method [14]. This may also lead to a more robust functioning of the infrastructure, even in the face of the projected reduction in water availability, when accompanied by a decrease of the water volumes supplied to the Segura River basin. This is an important finding of this Thesis, which suggests that the adaptation to climate change and sustainable water management should be combined in one framework, and that even under reduced water availability a shift of water management paradigm to a more sustainable one is still possible.

On the other hand, our results also suggest that even a complete disregard of the environmental needs for water would not secure the required water volumes by the Segura River basin in the future due to reduced water availability. The water managers in the Segura River basin would have to count with significantly reduced water volumes supplied from the Tagus River basin under all considered climate change scenarios and management options. It is also worth to mention, that the water transfer between the Tagus and Segura River basins requires technical maintenance, and the minimum water volumes, which would still assure its profitability, have to be estimated.

The allocation of water resources to nature can be a very powerful instrument to enhance the ecosystem health and ecosystem services [185]. However, in the arid and semi-arid regions like the Tagus River basin it may also be perceived by people as a waste of scarce resources [184], and may trigger political and societal conflicts. The managers in the Southern catchments have to adjust to the limits, imposed by the water availability [86,182]. The new water saving technologies, as well as further development of desalination technologies could be introduced in the region [186]. However, usage of the alternative water sources to improve only the water supply part of the water management puzzle is not a panacea, and it is also very important that the water management strategy reconsiders and reduces the water demands to address all aspects of the water resources scarcity problem.

The wok described in this Thesis has contributed to the Iberian and European case studies of the “IMPRESSIONS” Project (FP7).

5.2 Limitations of the applied methodology and open research questions

Less and less rivers in the developed regions like Europe are preserved in their pristine conditions – humans have water resources distribution in many catchments around the globe [10,147]. Therefore, the role of water management has gained an immense importance over the last decades.

The water management strategies that are based only on the historical knowledge about the hydrological conditions of a river have obviously helped to supply societies with clean and affordable water. They have also clearly shown that they may jeopardize the environmental state of many rivers in the world, and even lead to political conflicts over water resources in some regions. In addition, such strategies are challenged by climate change and related impacts on the water resources. There is a widely recognized need for implementation of the Integrated Water Resources Management IWRM strategies, which are oriented to both the current and future states of a hydrological system and aim to consider also the possible development of the social and economic system in the future. At the same time, such management strategies have to face significant challenges due to uncertainties associated with the changing state of the river basins in future. The key factor of interest for the current water management is to know how, in the best possible way, to profit from the past experience for the rapidly changing environmental future [46].

One of the ways to assess future conditions and support the IWRM is the use of computer models, which can simulate the state of a river basin under different scenario conditions in order to understand impacts of changing environmental conditions and human development, as e.g. was performed in this Thesis. When properly built, the models can provide necessary support for managers in planning and assessing the water resources and water infrastructure [5]. The model supported assessments can help water managers and stakeholders to understand how to manage old and install new water infrastructure, perform effective and environmentally-friendly allocation of water resources.

Even though the modelling and simulation techniques have rapidly occupied a large niche in the scientific and management spheres over the recent decades, and were accompanied by dramatic increase in the computational power, the use of hydrological and climate models in the water sector is still associated with several problems.

First, the uncertainties associated with the hydrological and climate modelling are significant and are of major interest for scientific community. As discussed in **Chapter 1**, the uncertainties in the assessment of hydrological impacts of climate change are originating from: scenarios of future socio-economic development, greenhouse gases (GHG) emissions and selection of Representative Concentration Pathways (RCPs), General Circulation Models (GCM), downscaling methods statistical or Regional Climate Models (RCM), the bias correction method, input data for hydrological model, structure of hydrological models and parameterization and calibration of hydrological model [187]. The uncertainties have to be accounted for and conveyed to stakeholders. In fact, the representation and communication of the uncertainty in the hydrological modelling is the only way to create robust projections that can be used for the water management sector [188].

In principle, the uncertainties can be classified into two types – aleatoric, or biases, which have statistical properties and epistemic, arising from lack of knowledge about a system. To reveal aleatoric uncertainty there are different statistical tools available, and the major goal about the epistemic uncertainty is either reduce it by gaining understanding about the system or to turn it into aleatoric [189].

With respect to uncertainty, coming from hydrological models, often the hydrological models are containing parameters, which values have to be estimated during the calibration of the model to the observed data. The adequacy of the chosen values for the unknown parameters is then checked during the validation phase. Here, already two problems are arising – first, with introduction of possible errors, that are coming from faulty recorded or treated observations and second, called non-uniqueness problem, when completely different sets of parameters values, not necessarily physically legitimate, give similar calibration-validation results. In fact, in this Thesis a deterministic approach for calibration was applied, meaning that the parameters of the model were adjusted in "trial and error" mode until, presumably, best calibration efficiency was reached. The uncertainty in the parameter estimation was not reported, which can be seen as a drawback and should be addressed in the future. There are several methods to reveal uncertainty, e.g. Sequential Uncertainty Fitting, SUFI 2 [190] or Generalized Likelihood Uncertainty Estimation GLUE [191]. In fact, the SWAT Model community has recently developed a module for automatic calibration of the SWAT Model, which includes the uncertainty estimation procedure, using different methods [192].

Further, as Montanari et al. [50] suggest, in order to take into account the elements of randomness in the hydrological system and to combine the uncertainty analysis and the hydrological modelling in one framework rather than just reporting the uncertainty ranges, it can be beneficial to combine the stochastic methods and process-based models in one framework. They suggest shifting from one simulation run of the deterministic model to many, each time using the stochastically perturbed input data, parameters and model outputs. This way the randomness of the natural system would be represented inside the model and in the scenarios.

The other way to visualize the uncertainty arising from the model structure is application of an ensemble of different hydrological models. A similar initiative has recently been taken by the regional modelling group of the ISI-MIP project [7,74] where several hydrological models, of global and regional scale were applied to 12 large river basins around the globe and the results of model performance for the calibration period, as well as for the projections simulation were compared. Results, reported by Hattermann et al. [7] show that global and regional different hydrological models driven by one GCM can give fairly different projections. At the same time such modelling exercise, involving several models and several climate change projections can result in larger model spreads in some regions, making the results and indication of change to be harder to convey to stakeholders.

It could be very interesting to combine the approach, proposed by Montanari et al. [50] within the SWIM model, for e.g. the Tagus River basin, and then compare the outputs to those from the ensemble of different hydrological models, as was done by Hattermann et al. [7].

For the case of climate models, there are several issues associated with application of their simulation outputs for the hydrological assessments. The scale mismatch between the climate models and the scales on which the water managers are operating is still significant. The water management decisions are taken locally, sometimes at the scale of a single water infrastructure unit, and the scale of hydrological models is much finer than that of GCM-RCM outputs. A coarse scale of GCMs also does not allow taking important orographic effects in the mountainous areas into account. Further, the climate models structure is still far from being perfect, there is little known about some processes, e.g. cloud formation, and interactions between them. There is evidence that the temperature patterns are well represented by the climate models in many regions of the world, on the contrary to the precipitation patterns, which still remain to be a challenging task for the models (IPCC, 2013).

The biases coming from the climate models, especially GCMs, have shown to be prevailing in the chain of models for the hydrological climate impact assessment when looking at the mean flows and high flows [45,48]. On the other hand, when considering the low flows, as Vetter et al. [45] discuss, the major source of uncertainty turns out to be the hydrological models. Consideration of the far future time period has also to be treated with caution when conveying the results to stakeholders, as the uncertainty in projections is increasing with time, also due to differences in the radiative forcing [45].

The uncertainty associated with the climate change modelling in this work was only revealed by the routinely applied "ensemble" approach, using multiple climate models projections to understand their agreements or disagreement on the trends. On the other hand, within the IMPRESSIONS scenarios the GCM-RCM models were selected to cover the different sensitivities of the climate models to the greenhouse gases forcing, potentially covering the full known spectrum of the models variety with respect to sensitivity. In the future, it would be better to perform a weighting of the models, by looking at their performance in the regions of interest instead of treating the models equally [193]. To understand and reveal the uncertainty associated with bias-correction, possibly a different method to the one used here (quantile mapping method) should be applied, and results compared.

Second, the hydrological models rarely simulate the anthropogenic influence and the co-evolution of human-hydrological systems. As was mentioned above, many rivers are not natural systems anymore and can be seen as human-hydrological systems, which are characterized by strong internal reciprocal interactions between their human and natural systems and these effects cannot be missed out. It is clear that the long-term assessment of the water infrastructure performance under changing conditions, e.g. changes in the inflows into reservoirs due to climate change effects, has to be performed considering also development in the socio-economic system. The changes in different water demands, additional water infrastructure that may be built in the catchment, urbanization and other land use changes may have a strong influence on the hydrological system. The International Association of Hydrological Sciences (IAHS) has declared its current research decade over the years 2013 - 2022 as "Pantha Rei" or "everything flows" [194], and recently many efforts were undertaken to represent the co-evolution of the hydrological systems and society, also called socio-hydrological systems [195]. Whereas representation of the hydrological part of the system can be performed comparably well with the available modelling tools, the human decision making process is hard to express in the modelling framework. There are several ways, as reviewed by Blair and Buytaert [196], to model the human decision making, including the agent-based modelling (ABM), systems dynamics, etc. However, any model with uncertainty in parametrization requires calibration or verification against observations and in the case of the human decision making the task becomes very complex. Even when a model is able to reproduce the past decision making process, there is no guarantee that it will also simulate correctly the dynamics under future conditions [196].

There is a clear limitation of the methodology applied in this Thesis for the assessment of the flow alterations, reservoir performance and water management strategies for the headwaters of the Tagus River basin under climate change. In the case of the entire Tagus River basin, the infrastructure and water demands will surely continue to develop in the future and this was not taken into account in this application, where it was assumed that the reservoirs and their management will be preserved in their current state. As for the headwaters of the Tagus River, the scenario-based approach can still provide an appropriate basis for the decision support system; however it cannot fully reveal the dynamics of the coupled human-hydrological system as the feedback from human part of the system is lacking. Especially in such rivers like Tagus with scarce water resources, where re-allocation of water to nature may have strong impacts on the social and economic conditions of the region, and also on dependent regions, as in this case – Segura River basin, it is important to account for the co-evolution of the socio-hydrological system.

To improve the applied methodology, it would be very beneficial to couple the SWIM model with e.g. an ABM model, which can represent the human decision making process, including water managers, hydropower beneficiaries and the farmers decision making on the land use and crops. One of the interesting examples on linking the ABM with a hydrological model is the study conducted by Tesfatsion et al. [197], where an ABM with five agents: farmer, city manager, market, climate and hydrology was developed to represent the human-decision making in a watershed over time. The model was focused on the interactions between the upstream farmer and downstream city manager and the effects of the different policies to reduce flood risk in the city (levee construction, subsidies for allocation of land to water-retention areas) on the welfare of two above mentioned agents.

Third, the research on water resources and river basin management has to involve professionals from different scientific areas and provide a continuous interaction with stakeholders [5,10]. Involvement of stakeholders at the initial stages of the project can be very beneficial in order to understand their concerns, needs and interests [5]. In fact, nowadays an efficient way to perform policy-targeted research could be to follow the marketing of science concept: e.g. in a similar way as marketing is targeting the needs of the consumers nowadays the applied science can follow this procedure, targeting the needs of stakeholders even before planning a project, and then base the research proposal on the expressed needs of the stakeholders. The science has to offer products that are required by managers, which reflect real life problems, and managers have to base their solutions on the best available information coming from the scientists. It could be very beneficial involving stakeholders at the initial stage of the project and in the model setup. Their field knowledge about the real water system under consideration can significantly improve the quality of the model setup [5]. On the other hand, the stakeholders could also understand more properly the technical side of the modelling framework and, e.g., the associated uncertainties and limitations.

Further, the transdisciplinary approach is a pre-requisite for a successful research and management of such complex systems like river basins. The involvement of scientists from different research areas is vital for understanding the effects of human activities in the basin [10]. The knowledge has to be linked with actions, providing sound scientific basis for the water managers and integrating the climate change risks into the water resources management strategies.

Therefore, it was valuable that the socio-economics scenario development in the "IMPRESSIONS" project was based on the stakeholder participatory approach - this allowed obtaining site-specific socio-economic scenarios and also taking into account the concerns of the stakeholders. Also, it was beneficial that the results of the study described in **Chapter 4** were highly policy relevant and have targeted the concerns expressed by the stakeholders. On the other hand, stakeholders were not directly involved in development of the management scenarios for the paper on the Tagus headwaters, which were rather based on the socio-economic projections obtained within the IMPRESSIONS project, and this can be a subject for improvement in the future.

Fourth, for an effective research, the observations, their quality, continuity and access to them are of a vital importance. Access to reliable data sources, their transparency and sharing between the scientific and stakeholders and policy makers community is extremely important for sustainable and effective water management solutions. In the case of the work conducted within this Thesis, the databases included global open source data, which are freely available in the internet. The data, obtained from the global databases, can require further refinement; especially in this case of soil information, as Harmonized World Soil Database used in this Thesis has relatively coarse resolution and no information on soil depth, which can have strong influence on the runoff formation.

Fifth, the concept of the environmental flows applied in this Thesis and required by the IWRM and WFD implementation has until now no strict guidelines on how exactly one can derive minimum flows required to preserve a river in the good ecological state, and what the "natural" state of the river is. There are several methods on the establishment of the environmental flows, starting from very complex habitat modelling approaches and finishing with the simple look up tables and rules of thumb that might include only a limited understanding of the environmental processes involved. The Indicators of Hydrological Alterations IHA method, applied in this Thesis, has gained a wide acceptance as a first approximation tool that can bridge the understanding gap between the hydrologists and biologists [14,168]. However, at the later stages in each particular case the establishment of the environmental flows should include not only statistical analysis of the flows in the past but should be a product of an interdisciplinary endeavor, including ecologists, hydrologists, biologists, social and economic scientists etc. Important is to highlight also that in the case of the headwaters of the Tagus, our analysis was based on the natural state of the river, which was nearly 60 years ago, and presumably the aquatic ecosystem has already adapted to the new conditions and changed completely its structure. Therefore, it is questionable if such outdated "natural" conditions are still natural for the river system at all and meaningful for the estimation of environmental flows.

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Appendix I Supplementary materials

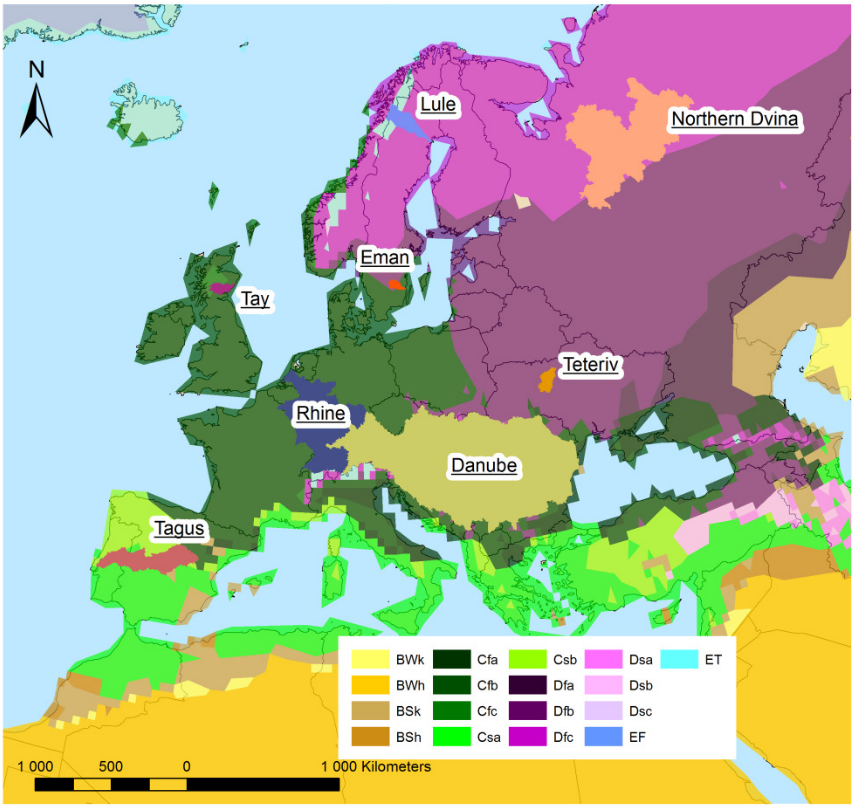

Figure A1. Koeppen Geiger climatic zones

Bwk	Cold desert climate	Cfa	Humid sub-tropical	Csb	Warm-summer Mediterranean climate	Dsa	Hot, dry-summer continental climate
Bwh	Hot desert climate	Cfb	Temperate oceanic climate	Dfa	Hot summer humid continental climate	Dsb	Warm, dry-summer continental climate
Bsk	Cold semi-arid	Cfc	Subpolar oceanic climate	Dfb	Warm summer humid continental climate	Dsc	Dry-summer subarctic climate
Bsh	Mild semi-arid	Csa	Hot summer Mediterranean climate	Dfc	Subarctic climate	EF	Ice cap climate
						ET	Mild tundra climate

Part A2

Tagus

The Tagus River has a total length of approximately 1000 km, a total drainage area of 80 000 km^2, and a mean discharge of 500 m^3/s at the outlet. One of the most important rivers on the Iberian Peninsula, it is the main water source for a number of large cities (e.g. Lisbon, Madrid), as well as for agricultural and industrial uses, and hydropower production [126]

Tay

The Tay River basin originates in the Scottish Highlands and is the longest river of Scotland, with approximate area of the catchment of 5 200 km^2. Average discharge of the river is around 170 m^3/s and is the largest river in the UK by the volume of the discharge measured. The river has a rich biodiversity and is of Site of Special Scientific Interest due its significant a rich ecosystem. There are significant industrial and irrigational abstractions, public water supply. The river has also a significant hydroelectric importance – there are many natural impoundments – Lochs which are nowadays regulated to produce energy. Tay is internationally known for its Atlantic salmon fishing and is of a great fishery importance. Precipitation varies between 1300 mm in the highland up to 700 mm in the lowlands.

Lule

Lule River is situated in the Northern Sweden; it originates in the Scandinavian Mountains and enters the Baltic Sea at the Bothian Bay. The basin area is approximately 25 000 km^2 and the river is 350 km long. The annual mean temperature of the catchment is -2.5^{o}C and the mean precipitation varies from 1000 mm in the upper northwest of the catchment reducing to 500-600 mm in the lower part of the catchment. Mean discharge of the river is approximately 500 m^3/s with peak flow typically happening in May or June. Snow processes are very important for this river. Due to impacts of climate change hydropower production can grow up to 34% Carlsson et al. 2005. However the identified impacts of the climatic change also may trigger much more floods.

Emån

Emån river is situated in the south of Sweden, is 220 km long and the average discharge of it is 30 m^3/s. The catchment is around 4500 km^2.

Dvina

Northern Dvina has a catchment area of 350 000 km^2 and the length is 744 km^2. Mainly this river has a snowmelt driven regime and the discharge at the outlet is 3500 m^3/s when entering the White Sea. The river has navigational importance and was the main Russian navigational route for trading before the emergence of the Saint-Petersburg.

Rhine

The Rhine River is one of the largest rivers in the central Europe. It takes its beginning the Swiss part of the Alps and drains area of 185 00 km^2 and enters the North Sea. Rhine River is of high importance for navigation and for irrigational water supply – in the Ruhr Area of Rhine the wines of a high quality are produced. The average precipitation is 700-1200 mm/y across the basin, which has highly heterogeneous conditions, from Alpines, snow driven regimes, when high peaks occurring during summer, when the snowmelt in the mountains take place and these conditions are buffered by large lakes, like lake Constance, to the pluvial regimes downstream, where high peaks occur more in winter. Mean annual discharge at the enter in the North Sea is approximately 2500 m^3/s.

Danube

The Danube River basin with the total drainage area of 817 000 km^2 is the second largest river basin in Europe. The river is crossing 19 countries and is the most international cross boundary river in the world. The basin is traditionally divided into three main parts Upper, Middle and Lower basins, which are characterized by different climatic conditions: Upper (Black Forest to Bratislava) – mainly Atlantic climate with high precipitation rates, Middle (Bratislava to Iron Gate) – continental climate conditions with relatively low precipitation rates and Lower basin (Iron Gate to the outlet) (see Stagl and Hattermann [77]). There are two largest dams Iron Gate I and Iron Gate II, with a volume of 2.1 km^3.

Teteriv

The Teteriv River basin is located in the Western Ukraine and covers approximately 15 000 km^2. It is one of the tributaries of the Dnipro River. The Teteriv River basin is characterized by continental climate, with average yearly temperature reaching 8.2 ^0C and mean annual precipitation 621 mm. The Teteriv River basin has important agricultural function, the main human withdrawals are for irrigation, pond-fishing, industry and a small share for domestic use.

Table A3 Wilcoxon p-values

Danube

RCP	RCP4.5		RCP8.5	
Period	**2041-2070**	**2071-2100**	**2041-2070**	**2071-2100**
Jan	0.293	0.945	0.003	0.000
Feb	0.050	0.054	0.000	0.000
Mar	0.562	0.649	0.003	0.000
Apr	0.001	0.001	0.002	0.005
May	0.000	0.000	0.000	0.000
Jun	0.001	0.000	0.006	0.006
Jul	0.017	0.011	0.100	0.042
Aug	0.004	0.004	0.134	0.552
Sep	0.000	0.000	0.075	0.799
Oct	0.001	0.002	0.077	0.170
Nov	0.022	0.020	0.208	0.130
Dec	0.230	0.098	0.562	0.142

Northern Dvina

RCP	RCP4.5		RCP8.5	
Period	**2041-2070**	**2071-2100**	**2041-2070**	**2071-2100**
Jan	0.127	0.002	0.000	0.000
Feb	0.055	0.003	0.000	0.000
Mar	0.000	0.000	0.000	0.000
April	0.000	0.000	0.000	0.000
May	0.011	0.014	0.003	0.000
Jun	0.016	0.033	0.005	0.005
Jul	0.022	0.095	0.016	0.002
Aug	0.623	0.552	0.343	0.275
Sep	0.959	0.799	0.854	0.115
Oct	0.786	0.616	0.467	0.583
Nov	0.467	0.080	0.001	0.028
Dec	0.273	0.037	0.000	0.000

Emån

RCP	RCP4.5		RCP8.5	
Period	**2041-2070**	**2071-2100**	**2041-2070**	**2071-2100**
Jan	0.018	0.017	0.000	0.000
Feb	0.003	0.001	0.000	0.000
Mar	0.009	0.063	0.000	0.000
April	0.665	0.185	0.959	0.357
May	0.786	0.275	0.328	0.694
Jun	0.192	0.896	0.686	0.326
Jul	0.219	0.740	0.003	0.060
Aug	0.382	0.426	0.000	0.023
Sep	0.612	0.501	0.050	0.033
Oct	0.994	0.170	0.248	0.236
Nov	0.138	0.871	0.018	0.029
Dec	0.028	0.255	0.000	0.000

Lule

RCP	RCP4.5		RCP8.5	
Period	**2041-2070**	**2071-2100**	**2041-2070**	**2071-2100**
Jan	0.000	0.000	0.000	0.000
Feb	0.000	0.000	0.000	0.000
Mar	0.000	0.000	0.000	0.000
April	0.000	0.000	0.000	0.000
May	0.000	0.000	0.000	0.000
Jun	0.000	0.000	0.000	0.000
Jul	0.000	0.009	0.000	0.000
Aug	0.003	0.007	0.000	0.000
Sep	0.000	0.000	0.000	0.000
Oct	0.000	0.000	0.000	0.000
Nov	0.000	0.000	0.000	0.000
Dec	0.000	0.000	0.000	0.000

Rhine					**Tagus**				
RCP	RCP4.5		RCP8.5		**RCP**	RCP4.5		RCP8.5	
Period	2041-2070	2071-2100	2041-2070	2071-2100	Period	2041-2070	2071-2100	2041-2070	2071-2100
Jan	0.006	0.003	0.005	0.000	Jan	0.843	0.391	0.011	0.000
Feb	0.005	0.006	0.000	0.000	Feb	0.741	0.255	0.040	0.000
Mar	0.005	0.002	0.000	0.000	Mar	0.366	0.067	0.001	0.000
April	0.350	0.004	0.001	0.000	April	0.343	0.037	0.000	0.000
May	0.040	0.001	0.005	0.000	May	0.192	0.033	0.000	0.000
Jun	0.994	0.224	0.809	0.147	Jun	0.192	0.029	0.000	0.000
Jul	0.809	0.573	0.552	0.032	Jul	0.300	0.050	0.000	0.000
Aug	0.623	0.728	0.390	0.118	Aug	0.266	0.034	0.000	0.000
Sep	0.266	0.160	0.797	0.616	Sep	0.307	0.024	0.000	0.000
Oct	0.100	0.095	1.000	0.408	Oct	0.039	0.004	0.000	0.000
Nov	0.936	0.908	0.192	0.015	Nov	0.138	0.004	0.000	0.000
Dec	0.458	0.013	0.034	0.000	Dec	0.947	0.562	0.000	0.000

Tay					**Teteriv**				
RCP	RCP4.5		RCP8.5		**RCP**	RCP4.5		RCP8.5	
Period	2041-2070	2071-2100	2041-2070	2071-2100	Period	2041-2070	2071-2100	2041-2070	2071-2100
Jan	0.007	0.000	0.000	0.000	Jan	0.005	0.002	0.000	0.000
Feb	0.001	0.001	0.000	0.000	Feb	0.001	0.002	0.000	0.000
Mar	0.023	0.242	0.014	0.001	Mar	0.096	0.012	0.016	0.003
April	0.665	0.000	0.697	0.001	April	0.423	0.195	0.321	0.318
May	0.924	0.009	0.119	0.065	May	0.286	0.156	0.242	0.063
Jun	0.106	0.020	0.676	0.180	Jun	0.665	0.616	1.000	0.463
Jul	0.523	0.072	0.582	0.583	Jul	0.602	0.542	0.936	0.660
Aug	0.260	0.104	0.236	0.009	Aug	0.366	0.365	0.959	0.275
Sep	0.335	0.261	0.971	0.531	Sep	0.854	0.728	0.476	0.054
Oct	0.809	0.453	0.138	0.001	Oct	0.138	0.156	0.001	0.006
Nov	0.177	0.013	0.119	0.000	Nov	0.119	0.009	0.000	0.000
Dec	0.070	0.000	0.000	0.000	Dec	0.130	0.004	0.000	0.000

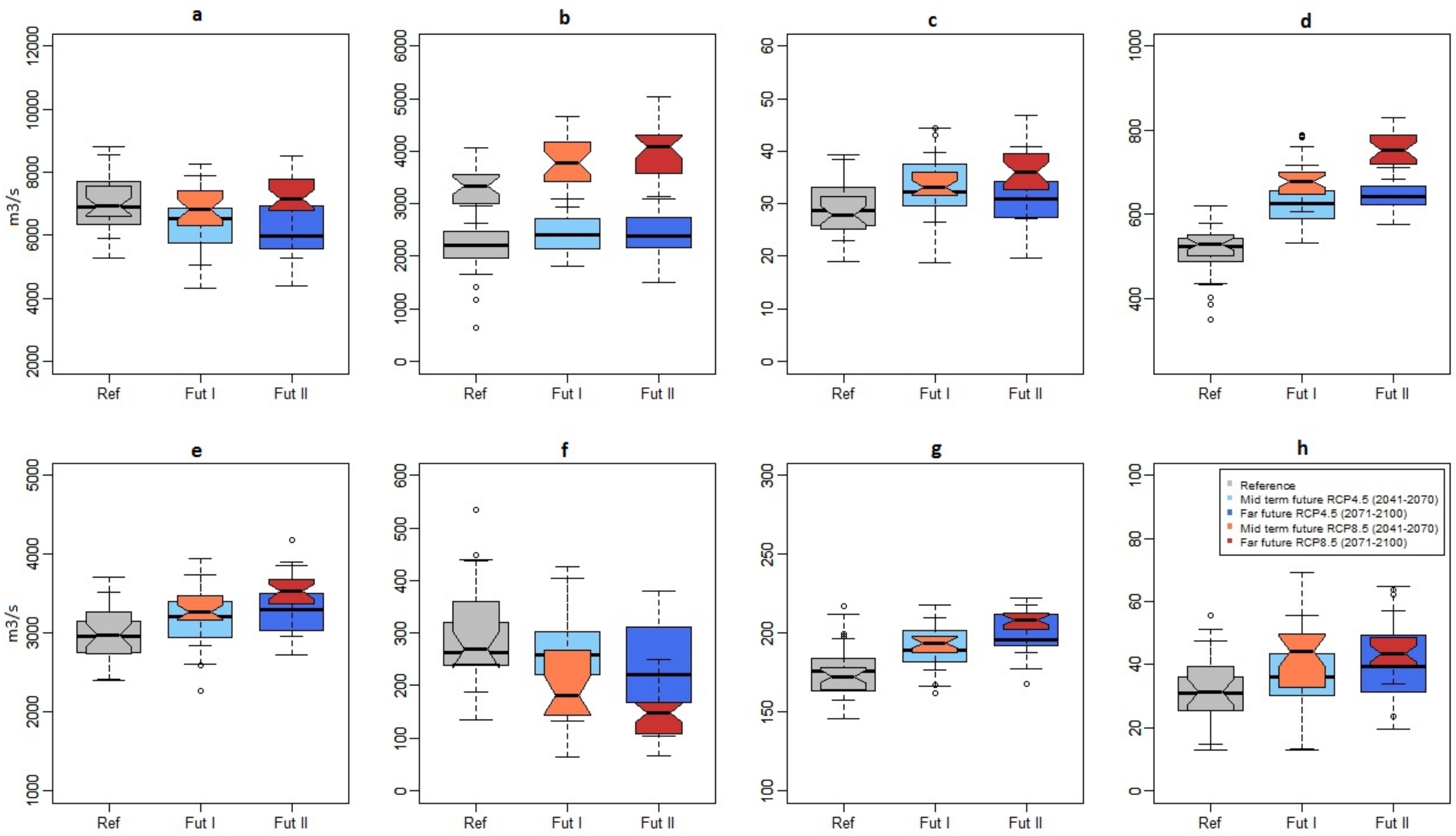

Figure A4. *Long-term mean annual river discharge for the reference, intermediate and far future time slices simulated with SWIM model, driven by the climate projections under RCP4.5and RCP8.5 scenario for the eight basins under consideration: a) Danube; b) Northern Dvina; c) Emån; d) Lule; e) Rhine; f) Tagus; g) Tay; h) Teteriv*

Table A5 Technical characteristics of the reservoirs under consideration

Characteristics	Reservoir		
	Buendía	Gabriel y Galan	Fratel
Constructed in	1973	1956	1973
Life Storage [hm^3]	1 651 hm^3	840 hm^3	32.5 hm^3
Total Volume [hm^3]	1 651 hm^3	911 hm^3	92.5 hm^3
Hydropower plant capacity	55.3 MW	110 MW	130 MW
Hydropower plant discharge	90 m^3/s	240 m^3/s	676 m^3/s
Head of hydropower plant	70 m	60 m	28.8 m
Name of the river	Guadiela	Alagon	Tagus (main)
Drainage area	3 318 km^2	1 856 km^2	60 000 km^2
Estimated turbine efficiency	0.89	0.81	0.91

Figure A6. Observed long-term mean annual river discharge at the Almourol gauge, vs. simulated by SWIM driven by the reference period of climate models vs simulated by SWIM driven by WATCH Era 40 dataset

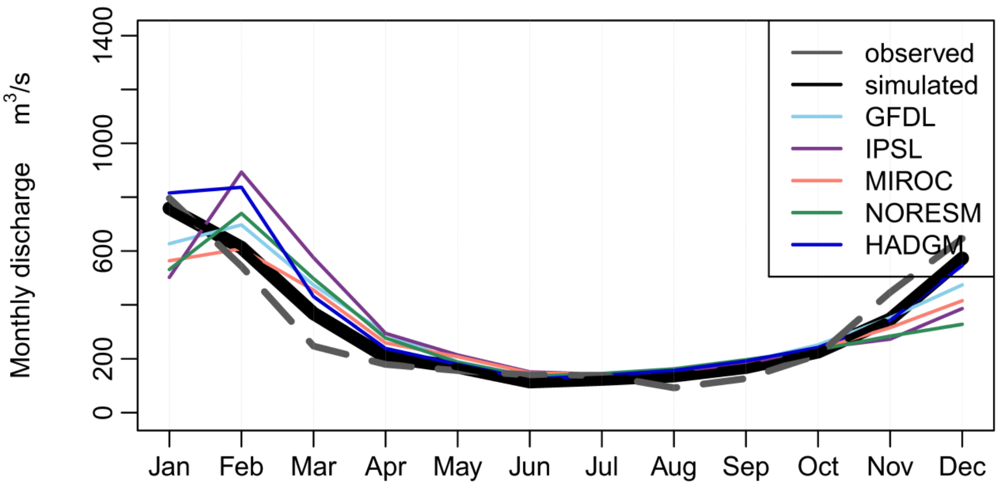

Table A7 Goodness of fit (R^2) between observed, simulated with WATCH and simulated with historical datasets of the GCMs long-term average monthly seasonal dynamics at the Tagus outlet (gauge Almourol) over 1987-1999 years

Model	GFDL-ESM2M	IPSL-CM5A-LR	MIROC-ESM-CHEM	NorESM1-M	HadGEM2-ES
Observed vs Climate models	0.74	0.40	0.71	0.49	0.81
Simulated vs Climate models	0.90	0.61	0.89	0.70	0.95

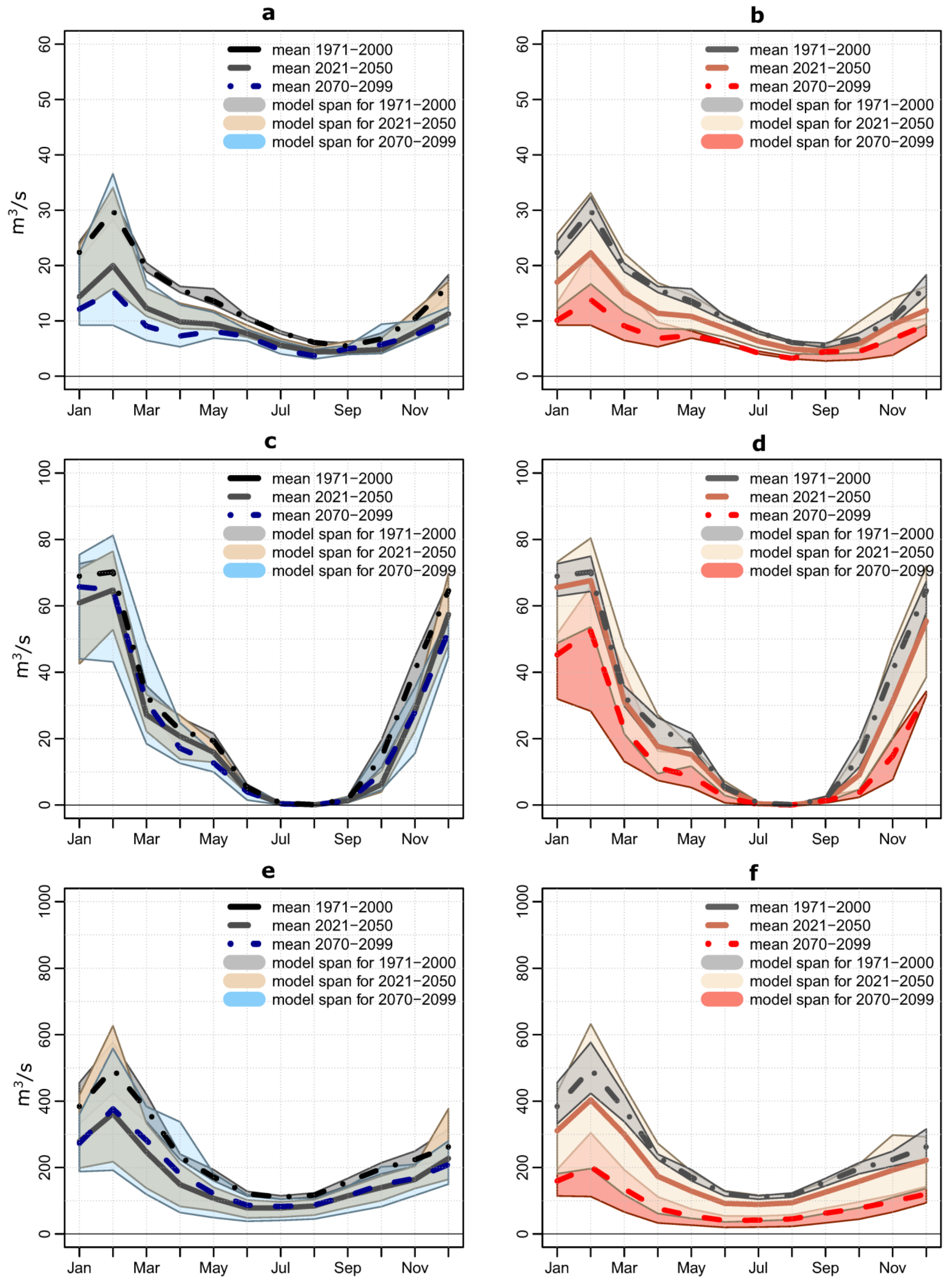

Figure A8. Average monthly inflows in m³/s into reservoirs in Buendía (a; b); Gabriel y Galan (c; d); Fratel (e; f) for reference, near and far future periods, under RCP4.5 (left) and RCP8.5 (right) warming scenario

Text A9. Current operational rule of the Tagus Segura Transfer

The monthly volume to be transferred to the Segura Rivera basin is estimated depending on the volumes stored in the Entrepeñas and Buendía reservoir at the beginning of each month. The total annual maximum of water to be transferred is 650 hm^3 in each water year and shall not be exceeded. The operational rule has four following levels, according to which the withdrawal rate is estimated:

Level 1 is given when the joint stocks in Entrepeñas and Buendía are equal to or greater than 1 300 hm^3, or when the joint contributions into these reservoirs over the last twelve months are equal to or greater than 1 200 hm^3. In this case a monthly transfer of 60 hm^3/month is authorized.

Level 2 is given when the joint stocks in the Entrepeñas and Buendía reservoirs are less than 1 300 hm^3 and the inflows recorded over the last twelve months are less than 1,200 hm3. In this case a monthly transfer of 38 hm^3/month is authorized.

Level 3 is assigned when the joint stocks in Entrepeñas and Buendía reservoirs at the beginning of each month are less than the values specified in the table below (in hm^3):

Oct	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
613	609	605	602	597	591	586	645	673	688	661	631

At this level, referred to an exceptional hydrological situation, the competent authority may authorize a transfer of up to 20 hm^3/month.

Level 4 If the joint stocks in Entrepeñas and Buendía reservoirs are less than 400 hm^3 no transfer can be approved.

Table A10 Observations used for the analysis of flow alterations downstream of the BE system

Gauge name and number (CEDEX database)	*Hydrological regime*	*Period of analysis*	*Misc*
Valdajos, 3909	Natural, before the construction of the Buendía - Entrepeñas reservoirs	1911-1948	Some significant gaps in the observations for the beginning of the century
Almoguera, 3009	Modified, after construction of the Buendía - Entrepeñas reservoirs but before the beginning of the Tagus Segura Transfer	1964-1977	
Zorita reservoir, 3008	Modified, after beginning of the TST and before the implementation of the WFD	1980-1999	Outflow from the run-of-the-river reservoir
Zorita reservoir,3008	Modified, after the implementation of the WFD	2001-2010	Outflow from the run-of-the-river reservoir

Text A11Input datasets used for the model set up

The subbasin map of the Tagus River basin was generated with the use of the Digital Elevation Model (DEM) obtained from the Shuttle Radar Topography Mission (SRTM) [198] of the Consultative Group for International Agricultural Research (CGIAR) Database with the resolution of 90 m. The Coordination of information on the environment CORINE database provided the raster land use dataset, obtained from LANDSAT mission, with resolution of 100 m and the European Soil Data Centre [37] - the soil data with the resolution 1000 m.

For calibration and validation of the SWIM model the gridded climate WATCH Forcing Data (WFD) [38] based on ERA40 re-analysis product [136] are used. The calibration and validation was performed at the gauge Almourol, in Portugal. The observed data at the Almourol gauge were obtained from the Sistema Nacional de Informação de Recursos Hídricos SNIRH database of the Portuguese Ministry of Environment over the period from 1984 to 1999. The WATCH climate contains all climatic variables needed to set up the SWIM model and cover the whole globe on a 0.5 degree grid, covering the entire 20th century. The WATCH dataset is a synthetically generated product, corrected to the real observations, detailed description of which is provided by Weedon et al. [38]. While the usage of real observations for the model set up may appear to be a better option, due to relatively coarse resolution of the WATCH Dataset as well as their "synthetic" nature, often the observed data are not easily accessible or are inconsistent and contain gaps. For the Tagus Model Setup, the observed climate data were offered by the AEMET office (Spain) and the SNIRH database (Portugal). However, both datasets contained serious gaps or was not long enough to calibrate the SWIM model. Also, only few stations provided solar radiation. Therefore, it was decided to apply the WATCH dataset.

Data used for parametrization of the reservoirs were obtained from the Tagus River basin Management Report provided by the Ministry of Environment of Spain [137] and from the SNIRH database for the Portuguese part, including the characteristic curves of the reservoirs. Used for calibration and validation of selected reservoirs observed inflows, outflows, and volumes in the reservoirs, were provided by Centro de Estudios Hidrográficos del CEDEX database and by the SNIRH database for Portugal.

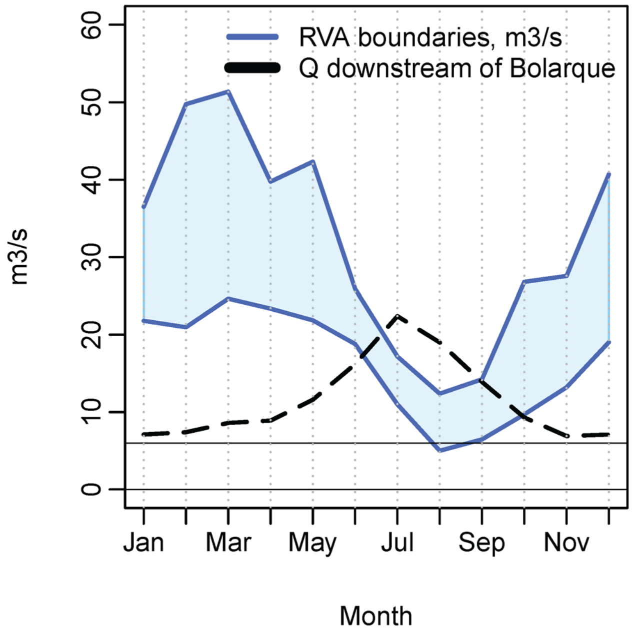

Figure A12 Range on the flows, recommended as the environmental flows by the RVA approach versus the flows at the Tagus proposed by the latest operational rule of the TST.

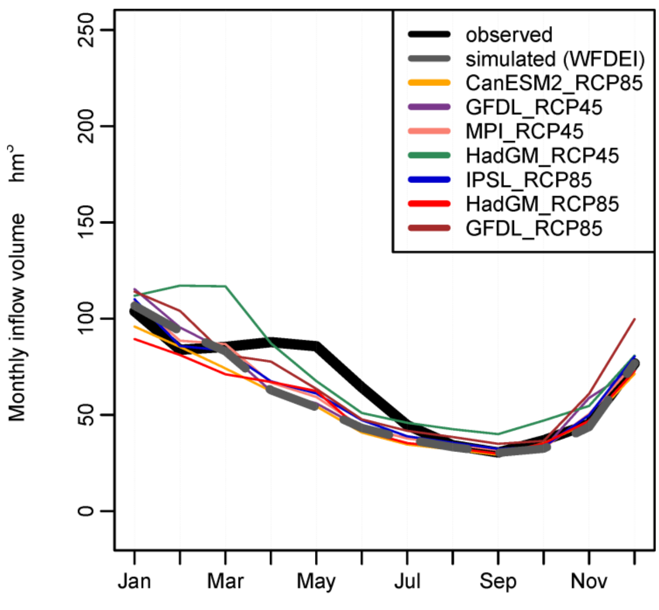

Figure A13 Inflows into B-E reservoirs observed, vs. simulated with SWIM driven by WFDEI and by reference period of climate models projections

Appendix II Reproduction of the modelling experiments

The issue of the reproducibility of the scientific experiments has recently gained significant attention within the scientific community, due to reported failure of more than 70% of researchers in different fields in reproducing scientific experiments, sometimes even their own [199] . The reproducibility is a key component to ensure transparency of the applied methods, as well as their robustness and, therefore, also the robustness of the results obtained.

The provision of access to raw data, modelling tools and developed scripts used for the experiments are essential to ensure the reproducibility of the results. In this Annex the links to the input data, used for the SWIM Model set up, calibration and validation, as well as climate data and climate projections are listed. All of the input data used for the current study were obtained from the open-access or access-upon-request databases available in the Internet.

Following data sources, also described in Chapter 2, 3 and 4, were used:

- Digital Elevation Model :
  - CGIAR http://srtm.csi.cgiar.org/
  - ASTER https://asterweb.jpl.nasa.gov/gdem.asp
- Soil Data: Harmonized World Soil Database
  http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/
- Land Use : CORINE Database
  https://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2000-clc2000-250-m-version-9-2007
- Discharge Data:
  - GRDC Global Runoff Database
    https://www.bafg.de/GRDC/EN/Home/homepage_node.html
  - SNIRH Sistema Nacional de Informação de Recursos Hídricos of Portugal
    https://snirh.apambiente.pt/
  - CEDEX Centro de Estudios y Experimentacion de Obras Publicas of Spain
    http://ceh-flumen64.cedex.es/anuarioaforos/default.asp
- Observed Climate Data:
  - WATCH Era Interim, WATCH Era 40

http://www.eu-watch.org/data_availability

- Agencia Estatal de Meteorología, AEMET, available upon request http://www.aemet.es/en/portada
    - SNIRH Sistema Nacional de Informação de Recursos Hídricos of Portugal https://snirh.apambiente.pt/

– Water Management Infrastructure Data
    - SNIRH Sistema Nacional de Informação de Recursos Hídricos of Portugal https://snirh.apambiente.pt/
    - CEDEX Centro de Estudios y Experimentacion de Obras Publicas of Spain http://ceh-flumen64.cedex.es/anuarioaforos/default.asp
    - SMHI Swedish Metrological and Hydrological Institute https://vattenwebb.smhi.se/modelarea/

– Climate Projection Data
    - ISIMIP Fast Track Data https://www.isimip.org/gettingstarted/data-access/ https://esg.pik-potsdam.de/search/isimip/
    - IMPRESSIONS Climate Data available upon request at Danish Metrological Institute DMI

- SWIM Model Source Code – latest version available upon request at swim(at)pik-potsdam.de.

In the supplied Electronic Supplementary for this Dissertation the SWIM Model set up, calibrated and validated for all eight river basins are supplied. Full description of the input files, output files and components of the SWIM Model can be found in the SWIM User Manual [200].

Below are provided examples of the input data, used for SWIM Model.

```
SWITCH PARAMETERS
0         isc            =0/1, SC: READ/CALC
1         icn            =0/1, CN: STANDARD / cnum1,cnum3 FOR ALL SOILS
0         idlef          =0/1, DAY LENGTH EFFECT IN CROP: WITHOUT/WITH
0         intercep       =0/1, INTERCEPTION: WITHOUT/WITH
0         iemeth         =0/1, EVAPORATION: Priestley-Taylor/Turc-Ivanov
0         idvwk          =0/1, EVAPORATION CALCULUS: DVWK-Merkblatt 238
1         res_switch     =0/1, reservoir module off/on
1         wat_allocate   =0/1, wam module off/on
1         subcatch       =0/1, subcatchment calibraton module off/on
________________________________________________________________________
BASIN, INITIALIZATION & CALIBRATION PARAMETERS
da        bff                                 BASIN PARAMETERS
68523.063 0.4748377
cnum1     cnum2     cnum3                     Curve number, if icn=1
56        60        81
ecal      thc                                 EVAPORATION PARAMETERS
1.3       1.0
gwq0      abf0      gwDelayDays               Groundwater parameters
0.42      0.413     25
ekc0      prf       spcon     spexp           Erosion parameters
1.0       1.000     0.0001    1.000
snow1     storc1    stinco                    Initial water storage
0.        0.5       0.55
chwc0     chxk0     chcc0     man             Channel parameters
1.1       1.5       0.1       0.55
roc1      roc2      roc3      roc4            Routing coefficients
0.        1.50000   0.        2.00000
sccor     prcor     rdcor                     Correction factors
1.001     1.00       1.0
retNsur   retNsub   retNgrw   retPsur         N & P RETENTION TIME
5.        365       15000     20.
degNsur   degNsub   degNgrw   degPsur         N & P DECOMPOSITION RATE
0.02      0.3       0.3       0.02
tsnfall   tmelt     smrate    gmrate          SNOW FALL&MELT PARAMETERS
0.0       0.0       0.25       1.8
xgrad     tgrad     ulmax0      rnew      raalf     precipitaiton and temperature elevation corrections
0.0000    0.0       1.0         0.08      0.0
maxUp                                         Riparian zone parameters
7
________________________________________________________________________
CO2 EFFECT ON NET PHOTOSYNTHESIS (alpha) & TRANSPIRATION (beta)
(ialpha,ibeta) = (1,0) OR (1,1) ONLY FOR SCENARIO PERIODS!
ialpha    ibeta     C3C4crop  CO2-ref   CO2-scen
0         0         3         346       406

0/1       0/1       3/4       346       406-436   OPTIONS & RANGES
________________________________________________________________________
```

*Figure A14. Example of the *.bsn file of the SWIM Model, containing calibration parameters for the modelled river basin (in this case Tagus River Basin, driven by WATCH Era Interim dataset)*

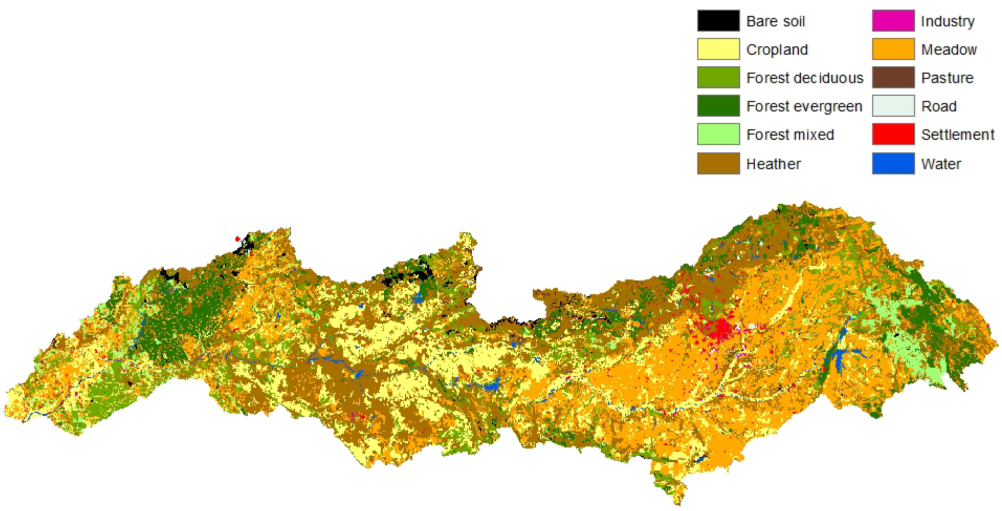

Figure A15. Land Use Map and its' classes for the Tagus River Basin

6970250.day

```
# Title:                   GRDC STATION DATA FILE
#                          --------------
# Format:                  DOS-ASCII
# Date format:             YYYY-MM-DD; YYYY-MM; YYYY; MM
# Field delimiter:         ;
#
# file generation data:    2015-11-17
#
# GRDC-No.:                6970250
# River:                   SEVERNAYA DVINA (NORTHERN DVINA)
# Station:                 UST-PINEGA
# Country:                 RU
# Latitude (dec. °):         64.150002
# Longitude (de. °):         41.916668
# Catchment area (km²):     348000.000
# Altitude (m.a.s.l):             2.00
# Next d/s station:        -
# Remarks:
#*************************************************************
#
# Data Set Content:        MEAN DAILY DISCHARGE
#                          --------------------
# Unit:                    m³/s
# Time series:             1883-01 - 2010-12
# No. of years:            128
# Last update:             2013-08-01
#
# Table Header:
#     YYYY-MM-DD - Date
#     hh:mm      - Time
#     Original   - original (provided) data
#     Calculated - GRDC modified data
#     Flag       - modification flag
#        -999 - missing data, no correction
#           1 - corrected data, no method specified
#          99 - usage not recommended by the provider
#         900 - calculated from daily water level
#
# Data lines: 46751
# DATA
YYYY-MM-DD;hh:mm; Original; Calculated; Flag
1883-01-01;--:--;   2050.000;   2050.000; -999
1883-01-02;--:--;   2090.000;   2090.000; -999
1883-01-03;--:--;   2100.000;   2100.000; -999
```

Figure A16. Example of one of the GRDC Station file for Ust'-Pinega gauging station, Northern Dvina River, containing daily discharge data