Water Resources in the Danube River Basin Under Scenarios of Agricultural Irrigation and Climate Change

Integrated Simulation Studies Using a Physically Based Land Surface Process Model

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View across the Danube River to the Small Island of Brăila

Romania, June 2019

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Summary

Water is a key requirement for life and continuously in motion in the global water cycle. Despite the enormous water quantities in the oceans, only a small fraction is available for humans as accessible freshwater. Spatial and temporal discrepancies between freshwater demand and availability lead to regional and seasonal water scarcity. In the future, water scarcity is likely to aggravate, as global water demand is expected to increase with a growing world population and regional and seasonal water availability is projected to alter with climate change. Water is at the center of sustainability efforts due to its key role for human well-being, socio-economic development and ecosystem functioning. The concept of the Water-Energy-Food-Ecosystem (WEFE) nexus postulates the close interdependence of water, energy and food security, and ecosystems. The water cycle and water flows in the WEFE nexus can be significantly altered by climatic and non-climatic factors, the latter mainly due to human land use interventions, which can create upstream-downstream water competition in river basins. Physically based, hydro-agroecological land surface process models (LSPMs), driven with historical or projected climate variables, are powerful tools for analyzing climatic and non-climatic effects on water flows, but require appropriate model setups and usually bias correction of meteorological forcing data.

The Danube River Basin (DRB) is an interesting study region due to its heterogeneity in terms of water availability and sectoral water use potentials for analyzing water flows under a changing climate or land use. Downstream countries are pursuing ambitious national plans for large-scale expansion of agricultural irrigation, which is expected to increase water demand. Simultaneously, current knowledge on climate change indicates alterations in water availability in the DRB, with wet regions and seasons becoming wetter and dry regions and seasons drier. This could put pressure on water resources in the DRB in the future.

This cumulative thesis focuses on water resources in the DRB between the poles of demand and availability under the looming future challenges of agricultural irrigation and climate change. In this work, upstream-downstream water competition in the WEFE nexus resulting from large-scale agricultural irrigation scenarios and the projected climate change impacts on water resources are assessed in the DRB. For this, the physically based, hydro-agroecological LSPM PROMET (Processes of Radiation, Mass and Energy Transfer) is used for simulation studies in the DRB, whereby the model setup and the meteorological forcings including their bias correction are evaluated. The methodological and application-oriented research questions of this thesis are addressed in three scientific papers.

In paper I, the methodological foundation of this thesis is built by establishing and validating a PROMET model setup for the heterogeneous DRB, which comprises a physically consistent parameterization and a land use/land cover (LULC) map with spatially distributed agricultural crops and their management. The suitability of the ERA5 global meteorological reanalysis and the derived WFDE5 forcing dataset for driving hydro-agroecological

PROMET simulations in the DRB is evaluated. For ERA5, the influence of linear bias correction using the global WorldClim 2 temperature and precipitation climatologies and the GLOWA and PRISM Alpine precipitation climatologies is assessed. Uncalibrated simulations show good model efficiencies and low percent biases of discharge at selected gauges. ERA5 and WFDE5 are suitable for driving PROMET in the DRB, but bias correction is essential for ERA5. GLOWA and PRISM outperform WorldClim 2 when used for bias correction in the Alps due to more realistic small-scale Alpine precipitation patterns resulting from higher station densities. This highlights the need for regional high-resolution precipitation climatologies rather than global data for bias correction in mountain regions.

In paper II, scenarios of agricultural irrigation in the DRB are simulated using the validated PROMET setup. Upstream-downstream water competition between agriculture, hydropower and aquatic ecosystems resulting from maize irrigation is analyzed and expressed as trade-offs in the WEFE nexus. Simulations include a rainfed maize scenario and scenarios assuming large-scale maize irrigation, where irrigation water is extracted from rivers and environmental flow requirements (EFRs) are either ignored or maintained. Maize yield and water use efficiency (WUE) increase by 125% and 34% compared to rainfed cultivation when the irrigation water demand of 12.9 billion m^3/a is fully met, resulting in a 1.9% reduction in hydropower production due to reduced discharges and substantial violations of EFRs that threaten aquatic ecosystems. Sustainable irrigation by maintaining EFRs limits extractable irrigation water amount to 6.5 billion m^3/a, resulting in 101% and 29% increases in maize yield and WUE, and a 1.0% reduction in hydropower production. The revenue gains in agriculture (5.8–7.2 billion €/a) exceed the losses in hydropower (23.9–47.8 million €/a). Irrigation WUE is highest for sustainable irrigation, indicating that keeping EFRs is economically beneficial. The most productive 35–41% of maize cropland could deliver the current maize production in the DRB through irrigation, allowing 59–65% to be spared for nature. Priority areas for maize irrigation are on fertile lowlands near major rivers, while priority areas for biodiversity are on marginal cropland with highest biodiversity intactness.

In paper III, the climate change impacts on water resources in the DRB are analyzed by driving the validated PROMET setup with an ensemble of EURO-CORDEX regional climate projections under the RCP2.6 and RCP8.5 emissions scenarios in the near (2031–2060) and far future (2071–2100), and in the historical reference period (1971–2000). Climate change impacts are moderate under RCP2.6 and intensify under RCP8.5, especially in the far future, exhibiting clear warming trends (RCP2.6: +1.2 °C in the near/far future; RCP8.5: +2.2 °C and +4.3 °C in the near/far future). RCP8.5 trends indicate increasing winter precipitation (+26.6% and +23.8% in the near/far future) and winter discharge in the Upper Danube and decreasing summer precipitation (–6.5% and –12.6% in the near/far future) and summer discharge in the Lower Danube, leading to decreasing summer soil water contents, increasing plant water stress and decreasing snow water equivalents. High flows become more frequent along the entire Danube River, while low flows become more frequent along the Middle and Lower Danube River. RCP2.6 trends are less distinct and tend to show increasing precipitation and discharge in most seasons, especially in the far future.

The findings of the three papers lead to the following main conclusions for the DRB:

1) The successful validation demonstrates the applicability of PROMET for hydro-agroecological simulations in the heterogeneous DRB. This requires an appropriate model setup (e.g. LULC information) to simulate land surface processes in their correct spatiotemporal arrangement. Avoiding empirical calibration increases confidence in the model's predictive power for, e.g. land use scenario or climate change impact studies.
2) Global meteorological reanalysis data are suitable to drive hydro-agroecological simulations in the DRB, offering flexibility in data-scarce regions. In the Alps, however, this requires bias correction with regional high-resolution precipitation climatologies based on high station density to adequately simulate the complex Alpine mountain hydrology, which also strongly influences river water availability downstream.
3) Maize irrigation could realize high yield potentials, but high water demand downstream causes nexus trade-offs. Sustainable river water availability can meet half of the demand and limits yield increases on Danube tributaries, creating water scarcity hotspots. River water use for agriculture is more profitable than for hydropower. Pairing efficient and sustainable irrigation is a win-win situation and key to mitigating trade-offs. Sustainable water and land use can reconcile terrestrial and aquatic ecosystem protection.
4) RCP8.5 trends show spatial and seasonal shifts in water availability from downstream to upstream and from summer to winter. Increasing water stress, decreasing summer discharges and more frequent high and low flows are likely to hamper agriculture, energy production and river navigability, and threaten aquatic ecosystems. Given the contrasting trends in water availability under RCP2.6 and RCP8.5, the DRB's water future is highly dependent on whether the 2 °C goal of the Paris Agreement is met.
5) Water resources in the DRB are likely to face increasing pressure in the future as a result of an increasing spatial and seasonal discrepancy between water demand due to agricultural irrigation and availability due to climate change, with particular hotspots in the Middle and Lower Danube agricultural lowlands. The impact of irrigation water extraction on the basin-wide water balance can be substantial compared to the impact of climate change. These trends are likely to aggravate nexus water competition.

The challenges associated with the anticipated trends in water demand and availability in the DRB call for science-based, integrated, transboundary, cross-sectoral and climate-resilient water and nexus management that ensures the efficient and sustainable allocation and use of water and land resources. Stakeholder dialogue and cooperation is needed to create synergies and minimize nexus trade-offs, to implement climate change adaptation measures and to stimulate upstream-downstream benefit-sharing strategies for spatially optimized water and land use throughout the DRB. For this, intelligent hydro-agricultural monitoring and forecasting systems can provide the scientific basis.

Zusammenfassung

Wasser ist eine Grundvoraussetzung für das Leben und im globalen Wasserkreislauf ständig in Bewegung. Trotz der enormen Wassermengen in den Ozeanen steht dem Menschen nur ein kleiner Teil als zugängliches Süßwasser zur Verfügung. Räumliche und zeitliche Diskrepanzen zwischen Süßwasserbedarf und -verfügbarkeit führen zu regionaler und saisonaler Wasserknappheit. In Zukunft wird sich Wasserknappheit voraussichtlich noch verschärfen, da ein zunehmender globaler Wasserbedarf aufgrund der wachsenden Weltbevölkerung erwartet und eine sich verändernde regionale und saisonale Wasserverfügbarkeit aufgrund des Klimawandels projiziert wird. Wasser steht im Zentrum von Nachhaltigkeitsbemühungen, da es eine Schlüsselrolle für das menschliche Wohlergehen, die sozioökonomische Entwicklung und die Funktionsfähigkeit von Ökosystemen spielt. Das Konzept des Wasser-Energie-Nahrungsmittel-Ökosystem-Nexus postuliert die enge Verflechtung von Wasser-, Energie- und Nahrungsmittelsicherheit sowie Ökosystemen. Der Wasserkreislauf und die Wasserflüsse im Nexus können durch klimatische und nicht-klimatische Faktoren erheblich verändert werden, wobei letztere vor allem auf menschliche Einflussnahme in Form von Landnutzung zurückzuführen sind, die in Flusseinzugsgebieten zu Wasserkonkurrenz zwischen Ober- und Unterliegern führen können. Physikalisch basierte, hydro-agroökologische Landoberflächen-Prozessmodelle, die mit historischen oder projizierten Klimavariablen angetrieben werden, sind leistungsfähige Werkzeuge zur Analyse klimatischer und nicht-klimatischer Effekte auf Wasserflüsse, erfordern jedoch geeignete Modellsetups und in der Regel eine Bias-Korrektur der meteorologischen Antriebsdaten.

Das Einzugsgebiet (EZG) der Donau ist aufgrund seiner Heterogenität in Bezug auf die Wasserverfügbarkeit und die sektoralen Wassernutzungspotenziale ein interessantes Untersuchungsgebiet, um Wasserflüsse unter einem sich verändernden Klima oder Landnutzungen zu analysieren. Die Unterliegerländer verfolgen ehrgeizige nationale Pläne zur großflächigen Ausweitung der landwirtschaftlichen Bewässerung, was den Wasserbedarf voraussichtlich erhöhen wird. Gleichzeitig deutet der derzeitige Kenntnisstand über den Klimawandel auf Veränderungen in der Wasserverfügbarkeit im Donau-EZG hin, wonach feuchte Regionen und Jahreszeiten feuchter und trockene Regionen und Jahreszeiten trockener werden. Dies könnte die Wasserressourcen im Donau-EZG in Zukunft unter Druck setzen.

Diese kumulative Dissertation beschäftigt sich mit den Wasserressourcen im Donau-EZG im Spannungsfeld zwischen Bedarf und Verfügbarkeit unter den sich abzeichnenden zukünftigen Herausforderungen durch landwirtschaftliche Bewässerung und Klimawandel. In dieser Arbeit werden die Oberlieger-Unterlieger-Wasserkonkurrenz im Nexus, die sich aus großflächigen landwirtschaftlichen Bewässerungsszenarien ergibt, sowie die projizierten Auswirkungen des Klimawandels auf die Wasserressourcen im Donau-EZG untersucht. Hierfür wird das physikalisch basierte, hydro-agroökologische Landoberflächen-

Prozessmodell PROMET (Processes of Radiation, Mass and Energy Transfer) für Simulationsstudien im Donau-EZG verwendet, wobei das Modellsetup und die meteorologischen Antriebsdaten einschließlich ihrer Bias-Korrektur evaluiert werden. Die methodischen und anwendungsorientierten Forschungsfragen dieser Dissertation werden in drei wissenschaftlichen Publikationen behandelt.

In Publikation I wird die methodische Grundlage für diese Dissertation geschaffen, indem ein PROMET-Modellsetup für das heterogene Donau-EZG erstellt und validiert wird, welches eine physikalisch konsistente Parametrisierung und eine Landnutzungs-/ Landbedeckungskarte (LULC-Karte) mit räumlich verteilten landwirtschaftlichen Fruchtarten und deren Bewirtschaftung umfasst. Die Eignung der globalen meteorologischen Reanalyse ERA5 und des daraus abgeleiteten Treiberdatensatzes WFDE5 zum Antrieb hydro-agroökologischer PROMET-Simulationen wird im Donau-EZG evaluiert. Für ERA5 wird der Einfluss einer linearen Bias-Korrektur unter Verwendung der globalen Temperatur- und Niederschlagsklimatologien WorldClim 2 sowie der alpinen Niederschlagsklimatologien GLOWA und PRISM untersucht. Unkalibrierte Simulationen zeigen gute Modelleffizienzen und geringe prozentuale Abweichungen des Abflusses an ausgewählten Pegeln. ERA5 und WFDE5 sind zum Antrieb von PROMET im Donau-EZG geeignet, wobei für ERA5 eine Bias-Korrektur unerlässlich ist. GLOWA und PRISM übertreffen WorldClim 2 bei der Bias-Korrektur in den Alpen aufgrund der realistischeren kleinräumigen alpinen Niederschlagsmuster, die sich aus höheren Stationsdichten ergeben. Dies unterstreicht die Notwendigkeit regionaler hochaufgelöster Niederschlagsklimatologien anstelle globaler Daten für die Bias-Korrektur in Gebirgsregionen.

In Publikation II werden landwirtschaftliche Bewässerungsszenarien im Donau-EZG mithilfe des validierten PROMET-Setups simuliert. Die aus Maisbewässerung resultierende Oberlieger-Unterlieger-Wasserkonkurrenz zwischen Landwirtschaft, Wasserkraft und aquatischen Ökosystemen wird analysiert und durch Trade-offs im Nexus ausgedrückt. Die Simulationen umfassen ein Szenario für Mais unter Regenfeldbau sowie Szenarien, die von einer großflächigen Maisbewässerung ausgehen, bei der das Bewässerungswasser aus Flüssen entnommen wird und ökologische Mindestabflüsse ($Q_{min,ök}$) entweder ignoriert oder eingehalten werden. Ertrag und Wassernutzungseffizienz (WUE) von Mais steigen im Vergleich zum Regenfeldbau um 125% bzw. 34%, wenn der Bewässerungswasserbedarf von 12,9 Mrd. m³/a vollständig gedeckt wird, was zu einem Rückgang der Wasserkraftproduktion um 1,9% aufgrund der reduzierten Abflüsse und zu erheblichen Verstößen gegen $Q_{min,ök}$ führt, wodurch aquatische Ökosysteme bedroht werden. Nachhaltige Bewässerung durch Einhaltung von $Q_{min,ök}$ begrenzt die entnehmbare Bewässerungswassermenge auf 6,5 Mrd. m³/a, was zu einem Anstieg von Maisertrag und WUE um 101% bzw. 29% und zu einem Rückgang der Wasserkraftproduktion um 1,0% führt. Die Umsatzsteigerung in der Landwirtschaft (5,8–7,2 Mrd. €/a) übertrifft den

Umsatzrückgang in der Wasserkraft (23,9–47,8 Mio. €/a). Die WUE der Bewässerung ist unter nachhaltiger Bewässerung am höchsten, was darauf hindeutet, dass die Einhaltung von $Q_{min,ök}$ wirtschaftlich vorteilhaft ist. Die produktivsten 35–41% der Maisanbaufläche könnten die derzeitige Maisproduktion im Donau-EZG durch Bewässerung abdecken, sodass 59–65% für die Natur freigegeben werden könnten. Vorrangflächen für Maisbewässerung liegen in fruchtbaren Tiefebenen in der Nähe großer Flüsse, während Vorrangflächen für Biodiversität auf Grenzertragsflächen mit intaktester Biodiversität liegen.

In Publikation III werden die Auswirkungen des Klimawandels auf die Wasserressourcen im Donau-EZG analysiert, indem das validierte PROMET-Setup mit einem Ensemble regionaler EURO-CORDEX-Klimaprojektionen unter den Emissionsszenarien RCP2.6 und RCP8.5 in der nahen (2031–2060) und fernen Zukunft (2071–2100) sowie im historischen Referenzzeitraum (1971–2000) angetrieben wird. Die Auswirkungen des Klimawandels sind unter RCP2.6 moderat und verstärken sich unter RCP8.5, insbesondere in der fernen Zukunft, und zeigen klare Erwärmungstrends (RCP2.6: +1,2°C in der nahen/fernen Zukunft; RCP8.5: +2,2°C und +4,3°C in der nahen/fernen Zukunft). Die RCP8.5-Trends deuten auf zunehmende Winterniederschläge (+26,6 % und +23,8 % in der nahen/fernen Zukunft) und Winterabflüsse im EZG der Oberen Donau und abnehmende Sommerniederschläge (–6,5 % und –12,6 % in der nahen/fernen Zukunft) und Sommerabflüsse im EZG der Unteren Donau hin, was zu abnehmenden Bodenwassergehalten im Sommer, zunehmendem Wasserstress bei Pflanzen und abnehmenden Schneewasseräquivalenten führt. Hochwasser werden entlang der gesamten Donau häufiger, während Niedrigwasser entlang der Mittleren und Unteren Donau häufiger werden. Die RCP2.6-Trends sind weniger eindeutig und zeigen für die meisten Jahreszeiten tendenziell zunehmende Niederschläge und Abflüsse, insbesondere in der fernen Zukunft.

Aus den Ergebnissen der drei Publikationen ergeben sich folgende wesentliche Schlussfolgerungen für das Donau-EZG:

1) Die erfolgreiche Validierung demonstriert die Anwendbarkeit von PROMET für hydro-agroökologische Simulationen im heterogenen Donau-EZG. Dies erfordert ein geeignetes Modellsetup (z.B. LULC-Informationen), um die Landoberflächenprozesse in ihrem korrekten raumzeitlichen Gefüge zu simulieren. Der Verzicht auf eine empirische Kalibrierung erhöht das Vertrauen in die Vorhersagekraft des Modells, z.B. für Landnutzungsszenarien- oder Klimafolgenstudien.
2) Globale meteorologische Reanalysedaten sind geeignet, um hydro-agroökologische Simulationen im Donau-EZG anzutreiben und bieten Flexibilität in datenarmen Regionen. In den Alpen erfordert dies jedoch eine Bias-Korrektur mit regionalen hochaufgelösten Niederschlagsklimatologien, die auf hoher Stationsdichte basieren, um die komplexe alpine Gebirgshydrologie, die auch die Wasserverfügbarkeit in den Flüssen stromabwärts stark beeinflusst, adäquat zu simulieren.

3) Die Bewässerung von Mais könnte hohe Ertragspotenziale realisieren, aber der hohe Wasserbedarf in den Unterliegern führt zu Trade-offs im Nexus. Die nachhaltige Wasserverfügbarkeit in Flüssen kann die Hälfte des Bedarfs decken und begrenzt Ertragssteigerungen an den Donauzuflüssen, an denen Hotspots der Wasserknappheit entstehen. Die Nutzung von Flusswasser für die Landwirtschaft ist profitabler als für die Wasserkraft. Die Kombination von effizienter und nachhaltiger Bewässerung ist eine Win-Win-Situation und ein Schlüssel zur Abschwächung von Trade-offs. Nachhaltiges Wasser- und Landnutzungsmanagement kann den Schutz terrestrischer und aquatischer Ökosysteme in Einklang bringen.
4) Die RCP8.5-Trends zeigen räumliche und saisonale Umverteilungen der Wasserverfügbarkeit von den Unter- zu den Oberliegern und vom Sommer zum Winter. Zunehmender Wasserstress, abnehmende Sommerabflüsse und häufigere Hoch- und Niedrigwasser werden voraussichtlich die Landwirtschaft, die Energieproduktion und die Schiffbarkeit der Flüsse beeinträchtigen und aquatische Ökosysteme bedrohen. Angesichts der gegenläufigen Trends in Bezug auf die Wasserverfügbarkeit unter RCP2.6 und RCP8.5 hängt die Zukunft des Wassers im Donau-EZG stark davon ab, ob das 2°C-Ziel des Pariser Klimaabkommens erreicht wird.
5) Die Wasserressourcen im Donau-EZG werden in Zukunft voraussichtlich einem zunehmenden Druck ausgesetzt sein, der aus einer zunehmenden räumlichen und saisonalen Diskrepanz zwischen Wasserbedarf infolge landwirtschaftlicher Bewässerung und Wasserverfügbarkeit infolge des Klimawandels resultiert, mit besonderen Hotspots in den landwirtschaftlichen Tiefebenen der Mittleren und Unteren Donau. Die Auswirkungen der Bewässerungswasserentnahme auf die einzugsgebietsweite Wasserbilanz können im Vergleich zu den Auswirkungen des Klimawandels erheblich sein. Diese Trends werden voraussichtlich die Wasserkonkurrenz im Nexus verschärfen.

Die Herausforderungen im Zusammenhang mit den antizipierten Trends in Bezug auf Wasserbedarf und -verfügbarkeit im Donau-EZG erfordern ein wissenschaftlich fundiertes, integriertes, grenzüberschreitendes, sektorübergreifendes und klimaresilientes Wasser- und Nexus-Management, welches die effiziente und nachhaltige Verteilung und Nutzung von Wasser- und Landressourcen sicherstellt. Dialog und Kooperation zwischen Stakeholdern sind notwendig, um Synergien zu schaffen und Trade-offs im Nexus zu minimieren, Anpassungsmaßnahmen an den Klimawandel umzusetzen und Strategien des Vorteilsausgleichs zwischen Ober- und Unterliegern für eine räumlich optimierte Wasser- und Landnutzung im gesamten Donau-EZG zu fördern. Intelligente hydro-landwirtschaftliche Monitoring- und Vorhersagesysteme können hierfür die wissenschaftliche Grundlage liefern.

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List of Abbreviations

AR	Assessment Report
CMIP	Coupled Model Intercomparison Project
CORDEX	Coordinated Regional Downscaling Experiment
DRB	Danube River Basin
DRBMP	Danube River Basin Management Plan
DRPC	Danube River Protection Convention
ECMWF	European Centre for Medium-Range Weather Forecasts
EFR	environmental flow requirement
ET	evapotranspiration
EU	European Union
EURO-CORDEX	Coordinated Regional Downscaling Experiment – European Domain
GCM	general circulation model
GHG	greenhouse gas
ICPDR	International Commission for the Protection of the Danube River
IPCC	Intergovernmental Panel on Climate Change
IWRM	Integrated Water Resource Management
LAI	leaf area index
LSPM	land surface process model
LULC	Land Use and Land Cover
NPP	net primary production
PROMET	Processes of Radiation, Mass and Energy Transfer
RCM	regional climate model
RCP	Representative Concentration Pathway
SDG	Sustainable Development Goal
SRES	Special Report on Emissions Scenarios
SSP	Shared Socio-economic Pathway
SWMI	Significant Water Management Issue
UN	United Nations
WEF	Water-Energy-Food
WEFE	Water-Energy-Food-Ecosystem
WFD	Water Framework Directive
WUE	water use efficiency

1 Introduction

1.1 The Point of Departure

1.1.1 Water as a Global Resource

Water is a key requirement for life, sustaining living organisms and ecosystems, and distinctly shaping the earth's surface. Seen from space, the water abundance on earth gives our blue planet its unique look (Mauser 2009). Approximately 71% of the earth's surface is covered with water (Babkin and Vuglinsky 2004). While 97.5% of the world's water resources are saltwater, most of which is stored in the oceans, only 2.5% are freshwater, mainly stored in ice caps, glaciers, permanent snow cover, groundwater and surface waters such as lakes and rivers (Shiklomanov 1993; 1997; 2009). Only 4% of the freshwater resources are directly accessible for human use and are stored in renewable groundwater reserves, lakes, rivers, wetlands and soils (e.g. Abbott et al. 2019; Douville et al. 2021).

Water on earth is in a continuous cycle driven by solar energy. This terrestrial water cycle comprises the water flows between the different compartments of the earth system (Mauser 2009). Water evaporates from oceans and land, is transported through the atmosphere as water vapor and can return to the earth's surface as precipitation (Pagano and Sorooshian 2002). On land, water can infiltrate into the soil, percolate into groundwater, evaporate from the soil or water bodies, be intercepted or transpired by plants, or flow as lateral (sub)surface runoff into rivers that eventually reach the oceans and close the water cycle (Pagano and Sorooshian 2002). Along the way, water can be stored for varying periods of time in lakes, glaciers, ice caps or groundwater (Pagano and Sorooshian 2002).

The water cycle is closely intertwined with the climate system, so that changes in the climate system affect the spatial and temporal availability of water on earth (UNESCO/UN-Water 2020). On the one hand, a warmer atmosphere can transport more moisture, making wet seasons wetter and rainfall events more intense, and on the other hand, rising temperatures increase the atmospheric evaporative demand and intensify droughts (Douville et al. 2021). Different warming levels over land and oceans alter global atmospheric circulation patterns, redistributing precipitation patterns and affecting soil moisture, river discharge and groundwater recharge (Douville et al. 2021; UNESCO/UN-Water 2020).

Alongside climatic factors, the water cycle is also influenced by non-climatic factors (Caretta et al. 2022; Douville et al. 2021). This is mainly due to the way humans use water resources. Direct human interventions include water abstraction from surface waters or groundwater for agricultural irrigation, industrial or other purposes, resulting in reduced river discharges and groundwater levels (e.g. Caretta et al. 2022). Indirect interventions include land use and land cover (LULC) changes, which also affect the water cycle by altering precipitation and evapotranspiration (ET) patterns (e.g. Caretta et al. 2022; Douville et al. 2021).

1.1.2 The Global Challenges

Due to the combined effects of climatic and non-climatic factors, it is estimated that half of the world's population (approx. 4 billion out of 8 billion people) are currently experiencing severe physical water scarcity for at least one month of the year (Caretta et al. 2022; Mekonnen and Hoekstra 2016). Physical water scarcity occurs when freshwater demand exceeds availability, taking into account the freshwater needs of ecosystems (Caretta et al. 2022; Mekonnen and Hoekstra 2016). Geographical and seasonal discrepancies between water demand and availability lead to varying degrees of water scarcity in space and time (Mekonnen and Hoekstra 2016). With a rapidly growing world population estimated to reach 9.7 billion by 2050 (UN 2022), global water demand is expected to increase by almost a third by 2050 (Burek et al. 2016; WWAP/UN-Water 2018). Main drivers of the increase in global water demand are the various dimensions and side effects of global change, such as – alongside population growth – economic development, improved living standards, changing consumption patterns, intensified agricultural production and irrigation, and expanding cities (e.g. Mekonnen and Hoekstra 2016; UNESCO/UN-Water 2020; Wada and Bierkens 2014). Climate change is projected to affect the quantity, geographical distribution and variability of water availability (Denton et al. 2022), as well as the water demand for different uses such as irrigation (Caretta et al. 2022), and is therefore likely to exacerbate water scarcity (UNESCO/UN-Water 2020).

The World Water Development Report 2020 of the United Nations (UN) highlighted that water is the key link in global efforts to achieve a sustainable future (UNESCO/UN-Water 2020). This is also reflected in the fact that water security is central to the 17 Sustainable Development Goals (SDGs) (Caretta et al. 2022) set by the UN as part of the 2030 Agenda for Sustainable Development (UN General Assembly 2015) in 2015. The 17 SDGs aim to achieve sustainable development worldwide, combining economic, social and environmental sustainability, and are simultaneously highly dependent on improved water management (UNESCO/UN-Water 2020). Water security is critical for human health and well-being, socio-economic development and ecosystem functioning (UN-Water 2013). Water is also central to the system transitions required for sustainable and climate-resilient development, including transitions in agricultural, energy, industrial, and urban systems (Caretta et al. 2022). However, water availability is seen as a major constraint to fulfilling future food and energy demands of a growing world population, making the interactions between water, food and energy systems in particular a key area of action to achieve a sustainable future (D'Odorico et al. 2018). In this context, the inextricable link between water security and food security is often highlighted, as agriculture is by far the largest user of water (see Section 1.2.3) (Caretta et al. 2022). This places a particular spotlight on agricultural and irrigation water management when it comes to water scarcity and the sustainable use of finite water resources.

1.2 Water in the Nexus

1.2.1 Key Concepts of the Nexus From the Water Perspective

The recognition that sustainable management of water resources is critical not only for the water sector alone had been around for some time and emerged in the late 1990s as the concept of Integrated Water Resource Management (IWRM) (Grambow 2013). The Global Water Partnership network defined IWRM as “a process which promotes the co-ordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems” (GWP 2000, p. 22), thus linking water management to societal, economic and ecological concerns (Grambow 2013).

However, IWRM was soon perceived as too narrow and water-centric to address emerging global food and economic challenges, leading to the development of the Water-Energy-Food (WEF) nexus concept (Weitz et al. 2017). The background paper for the Bonn 2011 Nexus Conference (Hoff 2011) is widely regarded as one of the landmark publications on the WEF nexus (UNECE 2018). The WEF nexus concept stipulates that water, energy and food security are closely interlinked, interacting and interdependent, and aims at integrated management and sustainable development across scales to reduce trade-offs and create synergies between the nexus pillars (Hoff 2011). Depending on the scope, the WEF nexus concept is often extended by other nexus pillars, e.g. to the Water-Energy-Food-Ecosystem (WEFE) nexus by integrating natural ecosystems to take into account their key role in ensuring human well-being and making human activities possible (Carmona-Moreno et al. 2019). Generally speaking, water and energy are needed to produce food, water is needed to produce energy, food can be used to produce energy, energy is needed to supply water, food transports virtual water (UNECE 2018), and natural ecosystems through their services create the basis for provisioning all these resources, but can be degraded by human activities (e.g. Fader et al. 2018; Karabulut et al. 2016). In contrast to water-focused IWRM, the nexus concept considers all components as equally important (FAO 2014).

Due to its integrative nature, the nexus concept is very well suited to inform actions and measures to support the achievement of the SDGs (UNECE 2018). UNECE (2018) highlighted four SDGs – the water goal (SDG 6), the energy goal (SDG 7), the food goal (SDG 2) and the life on land goal (SDG 15) – that are particularly connected in the nexus and, in some cases, include specific targets for river basins, which share common water resources. In particular, UNECE (2018) noted that SDG 6 involves sustainable water management and improving transboundary cooperation in river basins, SDG 7 includes providing access to sustainable and affordable energy, SDG 2 involves achieving food security and supporting sustainable agriculture, and SDG 15 includes protecting, restoring and sustainably managing natural ecosystems.

1.2.2 Water Flows and Upstream-Downstream Relations in a River Basin

River basins are well suited for analyzing the water flows within the WEFE nexus, as they are delineated hydrological units with a closed water balance that can be determined based on the easily measurable discharge at river gauges. In terms of water flows, the distinction between green and blue water is an important concept. While the green water flow is the water evapotranspired from the land surface to the atmosphere, the blue water flow is the surface and subsurface runoff flowing through rivers, lakes and aquifers, as well as the percolation of water into the groundwater (Falkenmark and Rockström 2006). Therefore, the green water resource refers to soil moisture and the blue water resource to water stored in surface water bodies and aquifers (Falkenmark and Rockström 2006). The green water flow can be divided into a productive part (i.e. transpiration of plants, which is involved in biomass production), and an unproductive part (i.e. evaporation from soils and water bodies and interception from plant leaves) (Falkenmark and Rockström 2006). In addition, consumptive water use corresponds to the water lost to the atmosphere through ET, resulting in a loss of water from the hydrological unit, whereas non-consumptive water use does not evapotranspire water, which can therefore be reused downstream (D'Odorico et al. 2018).

As briefly described in Section 1.1.1, the dynamics of the water cycle on the land surface can be significantly influenced by human interventions (Mauser 2009). This is to a considerable extent due to human land use decisions, which have a significant impact on the partitioning of water into green and blue water on the land surface (Mauser 2009). Such land use decisions include changes in, e.g. LULC (e.g. forest, grassland, cropland), crop type or agricultural management practices, which strongly influence (i) the partitioning of rainfall into soil infiltration and surface runoff (blue water), and (ii) the partitioning into ET (green water) and subsurface runoff and/or percolation (blue water) (Mauser 2009).

In this context, human interventions raise the importance of recognizing the relations between upstream and downstream water users in river basins (GWP 2000), which are connected by shared water resources. A vivid illustration of upstream-downstream water relations is the example of water competition between the two economic sectors of agriculture and hydropower. Green water consumed for agriculture upstream does not reach the rivers, cannot be reused (e.g. for agriculture, industry, energy production, households) and is unavailable for aquatic ecosystems downstream, whereas blue water used for hydropower upstream can still be reused for other purposes and is available for aquatic ecosystems downstream (D'Odorico et al. 2018; Probst et al. 2024). A special case is agricultural irrigation using surface water, where a certain amount of blue water (e.g. from rivers, lakes) is diverted to agriculture (and injected into soil water storage), of which a certain amount is evapotranspired as green water flow and is unavailable for other purposes or for aquatic ecosystems downstream (D'Odorico et al. 2018; Probst et al. 2024). This means that excessive water consumption upstream can deprive downstream users of their legitimate use of water, which inevitably raises the question of equitable sharing of common water resources and is particularly sensitive where large irrigation projects are planned upstream (GWP 2000). Dogaru et al. (2019) noted that irrigation in particular adds complexity to the nexus due to the comparatively large amounts of blue water that are converted to green water, linking food production to blue water availability. In light of this, Dogaru et al. (2019) further argued that irrigation is a special upstream-downstream issue and creates the strongest spatial interdependencies of all nexus factors.

1.2.3 Global Perspectives and Trends

Given the strong water-food link, the agricultural sector is a key field of action particularly for the food- and water-related SDGs. Agriculture is the most water-intensive economic sector, accounting for ~70% of global freshwater withdrawals and >90% of global freshwater consumption (FAO 2012), with the water footprint being composed of 78% green water and 12% blue water (Mekonnen and Hoekstra 2011). According to a recent review of food security projections, total global food demand is expected to increase by 30–62% between 2010 and 2050 (van Dijk et al. 2021) to feed a world population estimated to reach the aforementioned 9.7 billion people by 2050 (UN 2022), which will have direct implications for water demand (FAO 2012). Green water consumption by crops is projected to increase by ~12% between 1971–2000 and the 2090s due to the combined effects of climate and land use change (Huang et al. 2019). Projections of blue water demand for irrigation vary widely in numbers, depending on the assumptions made, ranging from a two- to threefold increase by the end of the century (Caretta et al. 2022). Ensuring food security with limited water resources is therefore a pressing challenge (e.g. D'Odorico et al. 2018). Key strategies to address these challenges include sustainable intensification, which aims to increase production on existing cropland while ensuring environmental sustainability (e.g. Garnett et al. 2013; Godfray et al. 2010), and precision agriculture, which aims to increase the resource efficiency of inputs (e.g. water, nutrients, pesticides) by applying them on-demand (e.g. Godfray et al. 2010). It has been shown that global biomass demand in 2050 can be met by closing yield gaps on existing cropland, which requires optimal management with increased cropping intensity, multiple harvests and a profit-maximizing crop allocation on farmland, thus making cropland expansion obsolete (Mauser et al. 2015b). In addition, empirical evidence shows that agricultural water use efficiency (WUE) (i.e. crop yield [kg] per evapotranspired water [m^3] in the growing season) increases with crop yield (Zwart and Bastiaanssen 2004), thus supporting the desirable strategy of “more crop per drop”. Efforts to close yield gaps on existing cropland are therefore a key objective in reconciling future food demand with resource-efficient water use.

The energy sector is far less water-intensive than agriculture, but is nevertheless critically dependent on water. In 2014, the energy sector accounted for 10% of global freshwater withdrawals and 3% of global freshwater consumption (IEA 2016). Energy-related water withdrawals are projected to increase by less than 2% between 2014 and 2040, but consumption is projected to increase by almost 60% (IEA 2016). Water demands for energy production vary widely and are highly dependent on the type of energy source (IEA 2016). While biofuels require large amounts of (green and blue) water for consumptive use (and also compete with food production), hydropower requires large amounts of blue water for largely non-consumptive use (when evaporation losses from reservoirs are neglected) (D'Odorico et al. 2018; IEA 2016). As of 2014, hydropower provides 16% of global electricity generation and more than 70% of global renewable electricity supply (IEA 2016), making it a key backbone of low-carbon electricity generation (IEA 2021) and the global transition to clean energy. Global hydropower capacity is expected to increase by 17% between 2021 and 2030, with reservoir hydropower plants accounting for the largest share of growth, followed by pumped storage and run-of-river hydropower plants (IEA 2021).

Natural ecosystems provide key ecosystem services, supplying water and other services critical to environmental, economic and social well-being (WWAP 2015). Wetlands, for example, mitigate floods, store water and provide habitats for fish (WWAP 2015). Forested highlands, to name another example, are essential for recharging aquifers, supplying clean water flows for agriculture, hydropower and other purposes, are crucial for biodiversity, water and soil conservation, and provide important habitats for wildlife (WWAP 2015). Both terrestrial and freshwater ecosystems have deteriorated rapidly since 1970, mainly due to land use changes (IPBES 2019; UN 2023). According to FAO/IWMI (2018), main pressures on the water balance of river basins are caused by, e.g. freshwater abstraction and drainage of agricultural land, threatening downstream wetlands (UN 2023). To date, more than 85% of natural wetlands have been lost (IPBES 2019; UN 2023). High current and projected future water demands in water-using sectors put pressure on water resources and related ecosystems, and raise concerns about the ability of water resources to meet the demands of future food production or the energy transition (e.g. Hogeboom et al. 2020). In this context, environmental flow requirements (EFRs) are often used as a measure for the water requirements of ecosystems and as a sustainability criterion, indicating the proportion of water required for the functioning and sustainability of freshwater-dependent ecosystems (e.g. Chiarelli et al. 2022; Karabulut et al. 2016).

1.3 Water and Climate Change

1.3.1 Key Concepts in Climate Change (Impact) Research

Moving on from non-climatic to climatic factors, a number of key concepts have been established over the past years and decades of climate change (impact) research. In this context, the Intergovernmental Panel on Climate Change (IPCC) has become a highly recognized institution whose reports are regarded by the scientific community as the most comprehensive and in-depth review of the current state of knowledge on climate change. Since its foundation in 1988, the IPCC has regularly synthesized the state of the art in climate change (impact) research in profound Assessment Reports (ARs). These reports outline possible climate futures based on different generations of greenhouse gas (GHG) emissions scenarios. Six ARs have been released to date, with the latest Sixth Assessment Report (AR6) (IPCC 2023) published in 2021–2023.

One of the more recent generations of GHG emissions scenarios are the Representative Concentration Pathways (RCPs) (Moss et al. 2010; van Vuuren et al. 2011), which served as the basis for IPCC AR5 (IPCC 2013), and for regional analyses in the latest AR6 (IPCC 2021). The RCP scenarios refer to the approximate total radiative forcing of GHG emissions – i.e. the additional amount of energy in the climate system – in 2100 compared to 1750 (IPCC 2013; Schwalm et al. 2020). A set of four main RCPs has been developed, consisting of RCP2.6, RCP4.5, RCP6.0 and RCP8.5, which represent radiative forcings of 2.6 W/m^2, 4.5 W/m^2, 6.0 W/m^2 and 8.5 W/m^2 (IPCC 2013). This set of scenarios includes a stringent mitigation scenario (RCP2.6), intermediate to high emissions scenarios (RCP4.5, RCP6.0), and a very high emissions scenario (RCP8.5) (IPCC 2013; 2023). While RCP2.6 assumes that atmospheric GHG concentrations (expressed as CO_2 equivalents) peak at 490 ppm around 2050 and decline to ~400 ppm by 2100, RCP8.5 assumes steadily increasing atmospheric GHG concentrations (CO_2 equivalents), reaching ~1370 ppm in 2100 (van Vuuren et al. 2011). RCP2.6 realizes most of its emissions reductions by reducing the carbon factor, which requires stringent climate policies, and by using bioenergy and carbon capture and storage technologies, ultimately resulting in negative emissions (van Vuuren et al. 2011). In contrast, RCP8.5 is a highly energy-intensive scenario due to high population growth and slower technological development, and is characterized by heavy reliance on fossil fuels, especially coal, and the absence of climate policies (van Vuuren et al. 2011). Although RCP8.5 has been controversially discussed as being too extreme and for showing unrealistically high coal emissions (Schwalm et al. 2020), a recent study by Schwalm et al. (2020) suggested that observed total cumulative CO_2 emissions between 2005 and 2020 are most consistent with the RCP8.5 pathway and argued that RCP8.5 is the most useful scenario for the mid-century time horizon and earlier. However, as Hausfather and Peters (2020) criticized, this consistency of RCP8.5 with near-term cumulative emissions is due to compensating errors of too high fossil CO_2 emissions and too low land use emissions.

The GHG emissions scenarios are regularly used to drive global climate or general circulation models (GCMs) and regional climate models (RCMs) to obtain global and regional projections of changes in the climate system (e.g. IPCC 2013; IPCC 2021) (see also Section 1.4.2). In the RCP2.6 mitigation scenario, global warming by 2100 is likely to be kept below 2 °C above pre-industrial levels (IPCC 2013; 2023), being in line with the 2 °C goal of the Paris Agreement (UNFCCC 2016) adopted at the 2015 UN Climate Change Conference held in Paris. In the very high emissions scenario RCP8.5, in contrast, global warming is likely to exceed 4 °C by 2100 (IPCC 2013; 2023), thereby far missing the Paris Agreement goals.

1.3.2 Global Perspectives and Trends

According to IPCC AR6, the observed mean global surface temperature has already increased by 1.09 °C in 2011–2020 compared to 1850–1900, with larger increases over land than over oceans (IPCC 2021), limiting the remaining buffer for the 2 °C and especially the 1.5 °C goal of the Paris Agreement (Probst and Mauser 2023). Global average precipitation over land is likely to have increased since 1950 (IPCC 2021), but the picture is much more complex than for temperature. Spatial patterns have already clearly shifted worldwide and major changes include increases or decreases in annual and/or seasonal precipitation in some regions, and a trend towards more frequent and intense extreme events, such as heavy precipitation and droughts (Caretta et al. 2022; Seneviratne et al. 2021).

Following the Clausius–Clapeyron relationship, every 1 °C of warming is associated with a ~7% increase in atmospheric water-holding capacity, which is often used as a rule of thumb to explain trends in heavy precipitation (Adam 2023; Douville et al. 2021). According to IPCC AR6, future projections indicate a further intensification of the water cycle due to an increased water exchange between a warmer land surface and the atmosphere (e.g. intensified convection processes) and resulting changes in atmospheric circulation patterns (Caretta et al. 2022). While the change in annual precipitation over the land surface is projected to be relatively small (±10% in most regions) at 1.5 °C global warming, this value increases to up to ±40% in most regions at 4 °C global warming (Caretta et al. 2022). However, the projected changes in annual precipitation vary substantially across the globe and are subject to considerable uncertainty in most regions, even regarding the sign of change (Caretta et al. 2022). For Europe, there is some consensus that precipitation will decrease in the Mediterranean (Caretta et al. 2022). In addition, the observed trend towards more frequent and intense extreme events (e.g. wet and dry spells) is projected to continue in the future (Caretta et al. 2022; Seneviratne et al. 2021).

Future ET over land is projected to increase with global warming and associated saturation deficits, but regional patterns are modulated by precipitation and hence soil water availability (Caretta et al. 2022; Douville et al. 2021). In addition, future ET is also influenced by the complex plant response to elevated atmospheric CO_2 contents, which includes a reduction in stomatal conductance and transpiration due to more efficient CO_2 uptake, but which can also be offset by the CO_2 fertilization effect, stimulating leaf area index (LAI) (Caretta et al. 2022; Douville et al. 2021; Skinner et al. 2017).

Future discharge is projected to increase overall with global warming, but shows significant regional and seasonal variations (Caretta et al. 2022; Douville et al. 2021). In most regions, the magnitude of the change in discharge is projected to increase with global warming, but again there is high uncertainty about the sign of change (Caretta et al. 2022). For only a few regions, the direction of trends is projected with higher confidence: e.g. for Europe, mean discharge is projected to increase in the northern high latitudes and decrease in the Mediterranean (Caretta et al. 2022).

1.4 State of the Art in Land Surface Process Modelling

1.4.1 Land Surface Process Models

Land surface process models (LSPMs) are highly useful for understanding and investigating the interactions of physical processes on the land surface, and more specifically, the dynamics that drive the fluxes of matter (e.g. water, carbon, nutrients) and energy under present and changing conditions. In sophisticated LSPMs, different components (e.g. meteorology, land surface, soil, vegetation, channel flow, groundwater) are typically coupled through the continuous exchange of mass and energy (Mauser and Bach 2009). For example, LSPMs partition surface shortwave (direct and diffuse) solar radiation into sensible, latent and soil heat fluxes as well as into reflected shortwave and emitted longwave radiation, and partition precipitation into ET (evaporation, transpiration, interception), (sub)surface runoff and infiltrated soil water fluxes (Douville et al. 2021; Mauser and Bach 2009).

The level of sophistication of the process descriptions in the different components is usually determined by the general purpose of the model. Classical hydrological models focus on the simulation of hydrological processes and include a river routing scheme, but vegetation processes are usually oversimplified (Douville et al. 2021; Hank et al. 2015). Classical crop models focus on the simulation of vegetation processes, but, in turn, hydrological processes are usually oversimplified (Zhang et al. 2021) and an appropriate river routing scheme is usually lacking. In addition, the investigated processes can be described either empirically or by simulation based on a mathematical (process based) description (Hank 2008).

In fact, the terrestrial energy, water and carbon cycles are closely coupled, e.g. through the photosynthetic activity of the vegetation cover (e.g. Betts et al. 2007; Gentine et al. 2019). The biophysical photosynthetic processes control the transpiration flux (adding up with the evaporation and interception fluxes to the latent heat flux) as well as carbon uptake, with soil moisture, vapor pressure deficit and atmospheric CO_2 content being important regulators of water and carbon fluxes (e.g. Gentine et al. 2019). Therefore, many authors called for intensified efforts in coupling hydrological and crop models (e.g. Siad et al. 2019; Zhang et al. 2021), but such studies are relatively rare and efforts are still at an early stage of development (Siad et al. 2019).

A sophisticated example of this type of coupled model is the spatially distributed, physically based, hydro-agroecological LSPM PROMET (Processes of Radiation, Mass and Energy Transfer) (Hank et al. 2015; Mauser and Bach 2009). PROMET goes beyond classical stand-alone hydrological or crop models by coupling the process descriptions of dynamic hydrological and biophysically based vegetation modelling, thus explicitly simulating the interactions and feedbacks between hydrological systems and vegetation activity (i.e. of natural vegetation and agro-ecosystems) (Hank 2008; Hank et al. 2015). In doing so, PROMET strictly conserves mass and energy as a whole and throughout all its components and interfaces (Mauser and Bach 2009), and runs at a high temporal (1 h) and spatial resolution (1 km² by default, finer possible). A very detailed description of the PROMET model theory and its different components can be found in Mauser and Bach (2009), Mauser et al. (2015a), Hank (2008) and Hank et al. (2015). In the following, a very brief overview of the model theory is given, with a focus on the hydrology-vegetation interactions.

Within the hydrology component, lateral water flows (i.e. surface flow, interflow, baseflow) are concentrated into river discharge and routed through the channel network using the mass-conserving Muskingum-Cunge-Todini method (Cunge 1969; Todini 2007), thereby closing the water balance (Mauser and Bach 2009). For this, routing coefficients are derived from physical channel characteristics (e.g. terrain, slope), which determine river discharge and flow velocities (Mauser and Bach 2009). Within the vegetation component, net photosynthesis, ET and net primary production (NPP) are calculated according to the biophysically based photosynthesis model for C_3 plants of Farquhar et al. (1980) (with extensions for C_4 plants according to Chen et al. (1994)) and the stomatal conductance approach of Ball et al. (1987) (Hank 2008). According to the phenology concept of Yin and van Laar (2005), assimilates are allocated to the plant organs depending on the phenological development stage (Hank 2008; Mauser et al. 2015b). NPP is sensitive to climatic and environmental factors such as meteorological variables, atmospheric CO_2 concentration, and water and temperature stress (Mauser et al. 2015b). For example, water stress inhibits stomatal conductance and thus plant transpiration, replicating the plants' reaction to water stress by closing the stomata (Hank 2008; Hank et al. 2015). In addition, PROMET explicitly accounts for human interventions through spatially distributed agricultural management practices such as crop sowing dates, fertilization, cultivar selection and irrigation (Hank 2008; Hank et al. 2015), including drip, flood and sprinkler irrigation. Irrigation follows a demand-driven approach, i.e. irrigation is triggered by water stress and irrigation water amount is determined by current soil water deficit (Cetin and Mauser 2023).

The process based calculation of plant transpiration is a key link between the hydrology and the vegetation component within PROMET, and considers, e.g. the influence of dynamic plant growth activity on water balance components (Hank 2008) and vice versa (see also Probst et al. (2024)). PROMET is therefore able to capture in an integrated manner the response of spatial domains such as river basins to climate change (Mauser and Bach 2009), LULC change or agricultural management intervention (Hank et al. 2015) such as irrigation, and the associated impacts on the spatial water balance. In the context of climate change, PROMET determines future trends in water balance and runoff generation not only as a function of changes in precipitation and temperature-dependent (and thus, saturation deficit-dependent) ET, but also through the dynamic response of plant transpiration to changes in temperature, soil water supply and atmospheric CO_2 concentration (Hank 2008). In the context of agricultural management interventions such as irrigation, PROMET determines the actual amount of transpired (green) soil water and irrigation water demand as a function of soil moisture and dynamic crop activity. The required irrigation water amount can be extracted from surface water sources such as rivers or from groundwater and is added to the soil water content, where it (partly) leaves the catchment through agricultural ET (thereby boosting yield formation) and is lost to rivers downstream (Probst et al. 2024). Recently, Probst et al. (2024) extended the demand-driven approach of irrigation water extraction from rivers with a decision scheme that imposes sustainability criteria upon crop irrigation and river water extraction, i.e. water extraction is allowed only if EFRs are maintained at the river site and all the way downstream. The interactions of all these mechanisms eventually determine agricultural production, surface water balance and runoff generation.

The ability to exchange fluxes of energy and matter on the land surface at the interface between atmosphere, soil, plants, rivers and human interventions makes PROMET a particularly integrated LSPM. Due to the foundation of PROMET on physical principles in all process descriptions, the model is parameterized based on information derived from spatial input parameters (e.g. terrain, soil), literature values or measurements, and empirical calibration is avoided as this would compromise the predictive power of the model as well as its transferability in space and time (Mauser and Bach 2009). The model's predictive power is based on the premise that physical processes remain unchanged under current and changing boundary conditions (Mauser and Bach 2009), making reliable studies of land use scenarios or climate change impacts just possible.

1.4.2 Meteorological Forcings

LSPMs are typically driven or forced with meteorological input data. Depending on scope and data availability, the meteorological forcings can consist of observed weather station data that are interpolated within the LSPM (e.g. Mauser and Bach 2009), or gridded datasets that are statistically downscaled within the LSPM (e.g. Marke et al. 2011; Marke et al. 2014).

One example of gridded meteorological forcings are fields of externally interpolated weather station observations at varying spatial and temporal resolution (e.g. Cornes et al. 2018). A second example of gridded forcings are historical reanalysis data, for which historical observations and remote sensing data are assimilated into numerical weather forecast models and thus represent the most coherent record of the historical global atmospheric circulation (Dee et al. 2011; Hersbach et al. 2020). A popular product is the ERA5 reanalysis (Hersbach et al. 2020) from the European Centre for Medium-Range Weather Forecasts (ECMWF), which comes at a spatial resolution of 0.25° and 1 h temporal resolution. A third example of gridded meteorological forcings are climate model data, such as from GCMs or RCMs (see Section 1.3.1). In contrast to reanalyses, climate models are free-running, i.e. they are not constrained by observations and follow their own model-specific dynamics (Maraun and Widmann 2018b). The Coupled Model Intercomparison Project (CMIP) is a well-known coordinator and distributor of GCM simulations, providing harmonized climate model outputs of standardized experimental protocols to facilitate comparisons between models (Eyring et al. 2016). GCM simulations of CMIP phase 5 (CMIP5) come at spatial resolutions of 0.5° to 4° and temporal resolutions of up to 3 h (Taylor et al. 2012). The global climate projections of the CMIP5 GCMs are based on RCP scenarios and were used in IPCC AR5.

Due to their coarse resolution, GCMs are dynamically downscaled using RCMs within a global coordinated framework (Coordinated Regional Downscaling Experiment; CORDEX) for regional domains, such as for Europe as part of the EURO-CORDEX initiative (Jacob et al. 2014). In the course of downscaling, RCMs are driven with GCMs at the lateral domain boundaries (Maraun and Widmann 2018a; Rockel 2015). The dynamical downscaling with RCMs is perceived as very valuable for better representing regional weather and climate phenomena, especially in regions with complex terrain (Doblas-Reyes et al. 2021). This is especially true for hydrological modelling purposes, for which finer-scale circulation patterns are required to adequately resolve hydrological processes (e.g. Maraun et al. 2010). The GCM-RCM simulations within EURO-CORDEX come at spatial resolutions of 0.11° (EUR-11) to 0.44° (EUR-44) and temporal resolutions of up to 1 h (Jacob et al. 2014). The regional climate projections of the EURO-CORDEX GCM-RCMs are also based on RCP scenarios and were used in the regional analyses in IPCC AR6.

Meanwhile, GCM simulations of the latest CMIP6 generation (Eyring et al. 2016) are available, which were used in the global analyses in IPCC AR6 and provide global climate projections based on the newer generation of Shared Socio-economic Pathways (SSPs) (O'Neill et al. 2014; van Vuuren et al. 2014). Efforts are currently underway to downscale the CMIP6 GCM simulations using RCMs to a new EURO-CORDEX CMIP6 generation (Katragkou et al. 2024; WCRP-CORDEX 2023). At the time of writing, it is not known yet when these data will be available; until then, the EURO-CORDEX CMIP5 generation is still the state of the art for regional climate projections.

1.4.3 Bias Correction

As outlined above, gridded meteorological forcings are statistically downscaled within the LSPM to its internal model resolution. However, the gridded forcings, in particular GCM/RCM data, but also reanalysis data, typically exhibit systematic spatial and temporal biases compared to observational reference data (e.g. Cucchi et al. 2020; Flato et al. 2013; Kotlarski et al. 2014; Muñoz-Sabater et al. 2021). Such biases can result from imperfect and simplified physical (circulation) process descriptions, and from the coarse resolution of the underlying models, which do not or rather inadequately represent sub-grid processes (e.g. Cucchi et al. 2020; Doblas-Reyes et al. 2021; Teutschbein and Seibert 2010).

Therefore, a bias correction routine is often included in the statistical downscaling step within the LSPM (Doblas-Reyes et al. 2021), in which the gridded forcings are corrected using an observational reference dataset (Maraun and Widmann 2018b). Since precipitation is considered a key meteorological driver for hydrological modelling, and as obtaining precipitation data of sufficient quality is often a challenge, bias correction of precipitation in particular is perceived critical for water-related simulations (e.g. Maraun et al. 2010; Muerth et al. 2013). For example, the bias-corrected WFDE5 forcing dataset has recently been derived from the ERA5 reanalysis, and was specifically developed for land surface and hydrological modelling applications (Cucchi et al. 2020).

Numerous bias correction methods exist, ranging from simple to more sophisticated approaches. Their peculiarities have been widely discussed, e.g. whether biases can be considered as time-invariant (i.e. stationary) or time-variant, which is particularly controversial for bias correction of future climate simulations (e.g. Doblas-Reyes et al. 2021; Ehret et al. 2012; Maraun and Widmann 2018b). A simple approach is linear bias correction, which corrects additive mean biases of temperature and relative mean biases of precipitation based on the difference or ratio of long-term mean monthly observed and modelled data (e.g. Maraun and Widmann 2018b; Teutschbein and Seibert 2012). Here, monthly climatologies can be used as observational reference, such as the frequently used global climatologies of WorldClim 2 (Fick and Hijmans 2017) or regional climatologies covering an area of interest (e.g. the precipitation climatologies GLOWA (Früh et al. 2006) or PRISM (Frei and Schär 1998) for the Alpine region). The approach of linear bias correction assumes stationarity, i.e. that the temperature and precipitation biases will remain constant also under future climate conditions (e.g. Maraun and Widmann 2018b; Teutschbein and Seibert 2012).

Apart from the extensive discussion on bias correction methods, the question of what role the observational reference dataset itself plays in the quality of bias correction has only recently been raised, although the observational uncertainty inherent in gridded precipitation data in particular is widely known (Gampe et al. 2019; Prein and Gobiet 2017) (see also Probst and Mauser (2022) for further explanations). In the Alpine region, for example, detailed comparisons of gridded precipitation observation datasets focused on the whole or part of the Alps (e.g. Gampe and Ludwig 2017; Haslinger et al. 2013; Isotta et al. 2015), Germany (e.g. Brienen et al. 2016) and Europe (e.g. Kotlarski et al. 2019; Prein and Gobiet 2017), with partly large discrepancies found between different datasets. In essence, the authors highlighted the importance of high underlying station density and undercatch correction for accurate precipitation estimates in mountainous terrain, and some of them also underlined the added value of high grid resolution of the datasets for resolving small-scale precipitation patterns. This is in line with common and widely recognized knowledge that major sources of uncertainty in observed precipitation data in mountainous terrain are mainly attributable to low station densities (e.g. Cornes et al. 2018; Fick and Hijmans 2017; Frei and Schär 1998; Hijmans et al. 2005; Isotta et al. 2015; Prein and Gobiet 2017), measurement errors such as precipitation undercatch (e.g. Frei and Schär 1998; Prein and Gobiet 2017; Sevruk 2006) and different interpolation approaches (e.g. Cornes et al. 2018; Fick and Hijmans 2017).

However, the well-known issue of observational uncertainty in gridded precipitation observation datasets has very rarely been considered in the context of bias correction; instead, an arbitrary selection of (a single) precipitation reference dataset for bias correction is usually made, as Gampe et al. (2019) and Prein and Gobiet (2017) criticized in the context of climate change impact studies. For example, Gampe et al. (2019) assessed the contribution of observational uncertainty in bias correction of RCM outputs to the overall uncertainty of RCM precipitation projections and found that using different precipitation reference datasets for bias correction strongly influenced precipitation projections in an Alpine catchment. Gampe et al. (2019) and Prein and Gobiet (2017) recommended taking observational uncertainty into account when bias-correcting RCM outputs by including multiple (pre-investigated) reference datasets, which according to Gampe et al. (2019) would contribute to obtaining more robust results in climate change impact assessments (see also Probst and Mauser (2022) for an overview). Addor and Fischer (2015) proposed to account for observational uncertainty in climate change impact studies by running the entire impact modelling chain using different reference datasets for bias correction of RCM outputs to explore the consequence on, e.g. hydrological modelling.

A related approach is often applied in hydrological modelling studies for historical periods to evaluate precipitation data. Given the measurement errors and the fact that there is no single best observational dataset reflecting the true precipitation values (e.g. Kotlarski et al. 2019; Prein and Gobiet 2017), a classical validation of precipitation data of any kind is rather challenging, especially over large areas (e.g. Reis et al. 2022). An elegant way to overcome this issue is to indirectly validate precipitation data within river basins by using them as a forcing for hydrological models and comparing modelled and observed discharge at river gauges, as discharge is much easier to measure than precipitation (provided, however, that sufficient discharge measurements are available) (e.g. Cucchi et al. 2020; Reis et al. 2022). In this sense, hydrological modelling could also be a promising tool for evaluating different precipitation reference datasets used for bias correction of historical precipitation forcings such as reanalysis data (thus accounting for observational uncertainty also in the historical context) in data-scarce mountainous terrain such as the Alpine region.

1.5 The Danube River Basin: An Interesting Study Region

1.5.1 Short Characterization of the Basin

The large transboundary Danube River Basin (DRB) (see Figure 1) is a very interesting river basin for conducting simulation studies on water-related issues due to its very heterogeneous natural and socio-economic characteristics, which lead to a complex situation of water resource availability and water use potentials in economic sectors. This section provides a brief characterization of the DRB, which is based on the study area descriptions by Probst and Mauser (2022), Probst et al. (2024) and Probst and Mauser (2023), where more detailed information can be found.

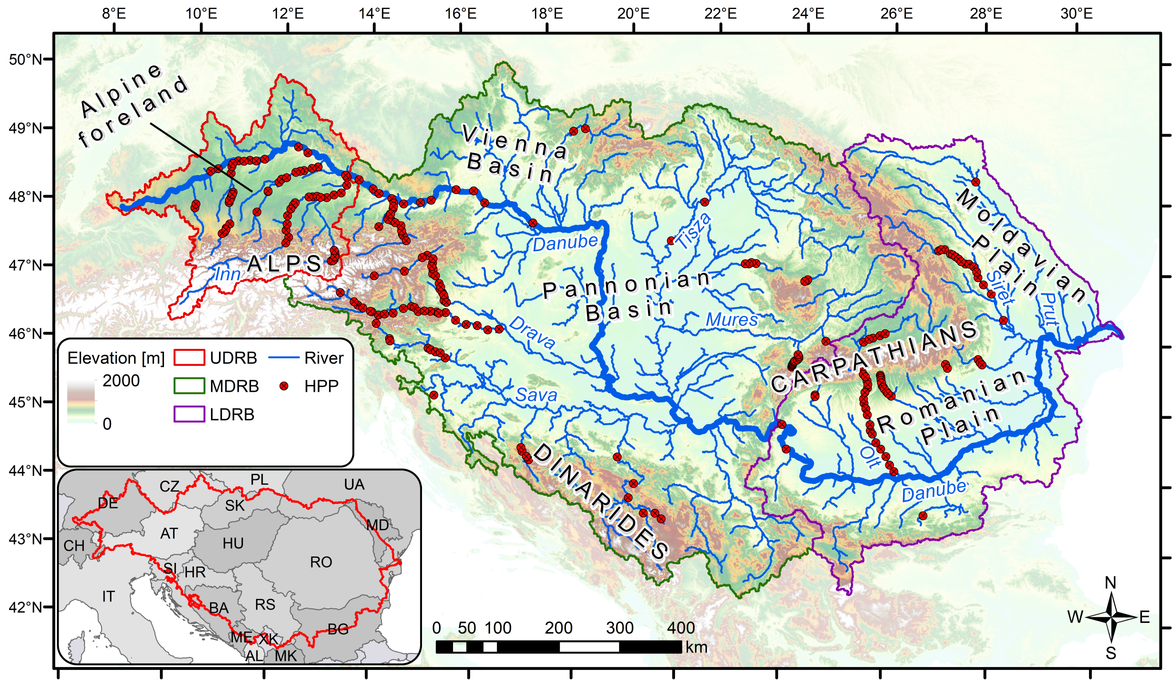

Figure 1: Map of the Danube River Basin with its river network, the division into the Upper Danube (UDRB), the Middle Danube (MDRB) and the Lower Danube (LDRB), and 234 large run-of-river hydropower plants (HPP) (≥10 MW). The overview map (bottom left) shows the 20 riparian countries (AL: Albania, AT: Austria, BA: Bosnia and Herzegovina, BG: Bulgaria, CH: Switzerland, CZ: Czech Republic, DE: Germany, HR: Croatia, HU: Hungary, IT: Italy, MD: Moldova, ME: Montenegro, MK: North Macedonia, PL: Poland, RO: Romania, RS: Serbia, SI: Slovenia, SK: Slovakia, UA: Ukraine, XK: Kosovo). Data sources: Farr et al. (2007), Lehner et al. (2008), GEO et al. (2018), EC and JRC (2019), NE (2024).

With a length of 2857 km from its source at the confluence of Brigach and Breg in the Black Forest to the Danube Delta at the Black Sea, a catchment area of ~817,000 km² and an average outlet discharge of ~6500 m³/s, the Danube River is the second longest and second largest European river, and has the second largest catchment in Europe (Jungwirth et al. 2014). The DRB is also the world's most international river basin (ICPDR 2021a), spanning over 20 riparian countries. The countries united in the DRB all rely on shared water resources as an economic resource, but were long divided by the Iron Curtain and still show socio-economic disparities (ICPDR 2011).

The DRB's heterogeneous topography, with mountain ranges such as the Alps, the Dinarides and the Carpathians, as well as basins and plains such as the Vienna Basin, the Pannonian Basin, the Romanian Plain and the Moldavian Plain, makes it a hydrologically very complex catchment. Major tributaries with a mountainous character include the Inn, the Drava and the Sava, while tributaries with (rather) a lowland character include the Mures, the Tisza, the Olt, the Siret and the Prut. In terms of climatic conditions, the spatial distribution of precipitation in the DRB is very uneven due to its diverse topography and the location in the transition zone between an Atlantic-influenced climate in the west and a continental climate in the east, resulting in a northwest–southeast gradient of decreasing precipitation (Schiller et al. 2010). While the Alps as water towers in the Upper Danube show high precipitation amounts, peaking at 3200 mm/a in the high mountain range, the Middle and Lower Danube lowlands show lower precipitation amounts, dropping down to 350 mm/a near the Black Sea (Schiller et al. 2010).

In the DRB, about 50% (i.e. ~45 million ha) of the area is under agricultural cultivation, and the vast lowlands of the Middle and Lower Danube, namely the Pannonian Basin, the Romanian and the Moldavian Plain, are among the most fertile regions in the northern hemisphere (ICPDR 2021b). Here, fertile soils (e.g. chernozems, soils with loess deposits) and warm temperatures create optimal farming conditions for thermophilic crops such as maize (Dogaru et al. 2019; ICPDR 2021b), which is the second most common crop in the DRB (EUROSTAT 2023). Agriculture is one of the most important rural employers in the eastern DRB (ICPDR 2021c). However, the Middle and Lower Danube lowlands are largely extensively used for agriculture (i.e. low and/or wasteful fertilization and irrigation, low levels of mechanization and highly fragmented parcels in some places) (Dogaru et al. 2019; ICPDR 2021b), which is in many regions due to the less favorable economic situation (ICPDR 2021c). In conjunction with recurrent droughts, this causes these regions to fall far short of their high agricultural potential, leaving large reserves for sustainable intensification (Dogaru et al. 2019; ICPDR 2021b). In the recent past, the DRB has experienced severe droughts in 2003, 2007, 2011, 2012, 2015, 2017–2020 (ICPDR 2021c) and most recently in 2022. During communist times, a large irrigation infrastructure consisting of a dense and extensive network of irrigation canals was built, especially in Romania, but was largely abandoned and fell into disrepair after the end of communism in Eastern Europe (Dogaru et al. 2019), coinciding with the collapse of agricultural outputs (ICPDR 2011). Currently, agricultural irrigation is at a very low level and accounts for only 1% of total water abstraction in the DRB (ICPDR 2021a), with irrigation water abstracted mainly from groundwater in the Upper Danube and from surface water in the Middle and Lower Danube (Siebert et al. 2013). In the Middle and Lower Danube countries, ambitious national irrigation plans are currently underway, aiming at large-scale rehabilitation and expansion of irrigation infrastructure (Dogaru et al. 2019), e.g. in Romania (DDD 2018; MADR 2019; World Bank Group 2018), Hungary (OECD 2021) and Serbia (MAEP 2015), which can significantly increase water demand in the long run. However, industry, energy production, transport and households are also critically dependent on the shared water resources in the basin (ICPDR 2021a).

In the DRB, hydropower is essential to the energy sector, accounting for 11% (excl. pumped storage) of total electricity production in the DRB countries (as of 2018) (Neubarth 2020). Hydropower is the most important component of total renewable energy production, contributing more than 45% in most DRB countries (except Germany, Hungary, Moldova) and even more than 90% in four countries (Bosnia and Herzegovina, Serbia, Romania, Slovenia) (ICPDR 2013b). With a total energy production of ~100 TWh/a (Feher and Muerth 2015; ICPDR 2013a), hydropower contributes indispensably to the energy transition in the

DRB and, being a domestic form of energy production, also to energy security within the basin (ICPDR 2013b). Geographically, the majority of hydropower plants are clustered in cascades along the (tributary) rivers of the Upper Danube with steeper gradients. The largest facility by far is the run-of-river hydropower plant complex Iron Gate I and II located on the Lower Danube River at the border between Romania and Serbia, supplying an average energy production of 2×5250 GWh/a and 2×1320 GWh/a (ICPDR 2005).

In addition, the DRB is a freshwater biodiversity hotspot, as its large west–east aligned catchment has ever since served as a freshwater species migration and recolonization corridor, connecting five European biogeographical regions (i.e. the Alpine, the Continental, the Pannonic, the Steppic and the Black Sea Region) (ICPDR 2005; Sommerwerk et al. 2009). The DRB hosts a unique variety of aquatic ecosystems, consisting of floodplains, marshlands, deltas and other wetlands, which are of tremendous value in providing habitats for rare species (ICPDR 2005) and which are mainly located along the Danube mainstream and its tributaries. The Danube Delta, Europe's largest remaining natural wetland, has been declared a transboundary UNESCO World Heritage Site (ICPDR 2005; 2011) and holds globally important breeding, feeding and resting sites for pelicans and 300 other bird species, as well as for sturgeons, river otters and many other endangered species (ICPDR 2005). However, aquatic ecosystems in the DRB face increasing pressure from agricultural, industrial and urban pollution, hydromorphological alterations such as impoundments and disruption of river continuity, as well as invasive species and overfishing (ICPDR 2005).

1.5.2 State of the Art in Water Management (Research) in the Basin

Water resources management in the DRB is coordinated under the direction of the International Commission for the Protection of the Danube River (ICPDR). Founded in 1998, the ICPDR is an international organization committed to the protection and sustainable and equitable management of water resources in the DRB under the framework of the Danube River Protection Convention (DRPC) (ICPDR 1998). Consisting of 15 contracting parties (14 DRB riparian states and the European Union, EU), the ICPDR has grown into the largest international expert body for river basin management in Europe (ICPDR 2014). The backbone of the ICPDR's operational work is formed by expert groups on, e.g. river basin management, flood protection, pollution-related pressures and water quality monitoring, composed mainly of experts and representatives of, e.g. national hydrological services, water management authorities and environmental ministries (ICPDR 2024).

When the EU Water Framework Directive (WFD) (EC 2000) came into force in 2000, setting a legal framework for the protection and improvement of the status of surface waters and groundwater, and for the sustainable use of water resources in the EU, the ICPDR countries (including the non-EU countries) agreed to implement the WFD throughout the DRB (ICPDR 2021a). The main objectives of the WFD are to achieve good chemical and ecological status for surface waters and good chemical and quantitative status for groundwater (EC 2000; ICPDR 2021a), thus having a strong ecological focus. In 2009, the ICPDR adopted the Danube River Basin Management Plan (DRBMP) (ICPDR 2009), which formulated measures for the implementation of the WFD and prescribed updates in the WFD's usual six-year cycles, such as 2015 (ICPDR 2015) and 2021 (ICPDR 2021a). The WFD's strong ecological focus is reflected in the DRBMP, which identified, e.g. pollution from excess nutrients or contaminants (esp. from agriculture) and hydromorphological alterations such as disrupted river continuity (esp. from hydropower) as the main threats to good water status and aquatic ecosystems in the DRB (ICPDR 2021a). The WFD considers the quantitative dimension of river discharges only as ancillary to water quality, more specifically through EFRs as a requirement for good ecological status of surface waters (Baranyai 2020b; ICPDR 2021a). The WFD has therefore often been criticized for not sufficiently addressing surface water quantity and water allocation issues, including their transboundary impacts, and for not taking into account the water demands of economic sectors other than the natural environment (e.g. Baranyai 2015; Baranyai 2020a; Carvalho et al. 2019) (see also Probst et al. (2024) for an overview).

Although water quantity issues still receive far less attention than water quality in DRB water management, awareness has steadily grown in recent years. In its Policy Paper on Sustainable Agriculture (ICPDR 2021c), the ICPDR expressed concern about the high agricultural water demand to meet the growing food demand, and that intensive agriculture can create quantity problems for water resources through over-abstraction of irrigation water, thus threatening the sustainability of water resources. It reaffirmed that irrigation practices must be WFD-compliant and called for efficient and sustainable irrigation systems (e.g. precision techniques, smart water saving methods) in the light of increasing droughts due to climate change (ICPDR 2021c). In the most recent DRBMP update in 2021 (ICPDR 2021a), climate change impacts – more specifically drought, water scarcity and extreme hydrological phenomena – were added to the list of Significant Water Management Issues (SWMIs), alongside the almost exclusively ecological issues. This is the result of integrating no-regret and low-regret adaptation measures from the revised ICPDR Climate Change Adaptation Strategy 2018 (ICPDR 2019) into the 2021 DRBMP update and means that WFD measures must be climate-resilient, i.e. also effective under increasing water scarcity or drought risk (ICPDR 2021a). In light of climate change, ICPDR (2019) recently highlighted the need for consultation on water competition between water-dependent sectors (e.g. agriculture, navigation, water supply, energy, industry, tourism, environment and nature protection) to take trade-offs into account. However, ICPDR (2021c) acknowledged that proper intersectoral dialogue, especially between the water and agricultural sector, and coordinated policy instruments are still to be established at the regional level of the DRB.

The strong ecological focus is also apparent in research on water management issues in the DRB, which has traditionally been very focused on (nutrient) pollution and hydromorphological alterations, whereby emerging challenges such as climate change and sediment management have recently received more attention (Feldbacher et al. 2016). The majority of research has been conducted in the areas of navigation, river restoration and biodiversity (Feldbacher et al. 2016).

More recently, some studies explicitly addressed water allocation and nexus issues in the DRB. Bisselink et al. (2018b) simulated future water scarcity in the DRB based on projections of climate change, water demand and land use, and found that climate change is the dominant driver of water scarcity. As far as described, however, no assumptions were made about a potential expansion of presently limited irrigated areas (Bisselink et al. 2018a; Bisselink et al. 2018b). Bisselink et al. (2018b) highlighted the importance of balancing water availability and demand for sectors such as agriculture (incl. irrigation), energy, industry, navigation, and domestic use, and that the WEFE nexus concept is a novel way to address such interlinked water allocation issues. Similarly, Baranyai (2015) and Pistocchi et al. (2015) emphasized the need for cross-border cooperation in the DRB in view of the competition for shared water resources. For the Sava sub-basin, UNECE (2016) stated that water competition between agricultural irrigation and hydropower generation can lead to trade-offs, and argued that estimating trade-offs is vital to identify relevant fields of action. De Roo et al. (2016) (as also presented by UNECE (2016)) made initial efforts to quantify the reduction in hydropower generation as a result of irrigation water abstraction in the Sava basin, but the described changes in agricultural production and hydropower generation were not directly linked to each other. Similarly, for the entire DRB, robust quantitative estimates of the trade-offs between agriculture and hydropower resulting from the implementation of large-scale agricultural irrigation have yet to be made (see also Probst et al. (2024) for an overview).

In a recent review, Dogaru et al. (2019) assessed the current situation of irrigation water use and national irrigation regulations in the DRB countries against the backdrop of the WEF nexus. The authors highlighted the need for integrated transboundary irrigation management in the DRB that explicitly accounts for trade-offs between water-using sectors and for the complex dynamics within the WEF nexus, and called for transdisciplinary nexus research in the DRB (see also Probst et al. (2024) for an overview). For this, Dogaru et al. (2019) raised interesting research questions that have not yet been addressed in the DRB. These include investigating whether water availability can sustainably meet countries' increased water demand due to irrigation expansion, where hotspots of water scarcity will emerge, and how climate change will affect the availability-demand relation (Dogaru et al. 2019). In addition, it is yet unclear how irrigated cropland can be allocated in an optimal and sustainable way within the DRB (Probst et al. 2024). Such questions are becoming more pressing in the face of potential irrigation expansion and climate change in the DRB.

1.5.3 State of the Art in Climate Change Impact Research in the Basin

The observed and projected impacts of climate change are not evenly distributed around the world but are spatially very heterogeneous, as is the case in the DRB. According to the global climate projections of IPCC AR5, a global mean temperature increase of +2 °C and +4 °C compared to 1850–1900 under the high emissions scenario RCP8.5 translates into a higher mean temperature increase of +2.5 °C and +5.2 °C in the DRB (Gutiérrez et al. 2021; Iturbide et al. 2021).

The revised Climate Change Adaptation Strategy 2018 of ICPDR (2019) mentioned above was based on a profound review by ICPDR/LMU (2018) (with overall findings also summarized by Stolz et al. (2018)), which compiled available case studies on projected climate change impacts on water resources in the DRB. Here, projected changes in temperature and precipitation were evaluated using EURO-CORDEX regional climate projections at their native spatial resolution (ICPDR 2019; Stolz et al. 2018). Under RCP8.5, for example, mean annual temperature in the DRB is projected to increase by 1.3–1.7 °C until 2050 and by 4.0–5.0 °C until 2100 compared to 1981–2010 (ICPDR 2019). In contrast to the clear warming trends, precipitation trends are less distinct and subject to higher uncertainties due to the DRB's location in a north–south transition zone between increasing (northern DRB) and decreasing (southern DRB) precipitation projections (Bisselink et al. 2018a; Bisselink et al. 2018b; ICPDR 2019). General trends were identified of (i) wet regions becoming wetter and dry regions drier, resulting in a strong northwest–southeast precipitation gradient, and (ii) winters becoming wetter and summers drier (ICPDR 2019; Stolz et al. 2018) (see also Probst and Mauser (2023) for an overview).

The projections available in the literature on the climate change impacts on discharge that consider the whole DRB show a wide and partly contradictory range of trends (e.g. Bisselink et al. 2018a; Di Sante et al. 2021; Stagl and Hattermann 2015; 2016). For mean annual discharge in the DRB, some found slight increases based on regional climate projections (e.g. Bisselink et al. 2018a), while others found (stronger) decreases based on global climate projections (e.g. Stagl and Hattermann 2016) (see also Probst and Mauser (2023) for an overview). These considerable uncertainties are largely due to the (less clear) precipitation projections and the location of the DRB in the transition zone between increasing and decreasing projections mentioned above. Di Sante et al. (2021) showed that the projected discharge trends across Europe strongly depend on whether global or regional climate projections (and which generation of emissions scenarios) were used, which in the case of the DRB leads to either northward or southward shifts of the transition zone. In general, common trends show spatial and seasonal changes in discharge, with seasonal discharge in particular shifting towards increasing winter discharges and decreasing summer discharges (e.g. ICPDR 2019; ICPDR/LMU 2018; Stolz et al. 2018). In most (case) studies, especially the Lower Danube experiences decreasing summer discharges under RCP8.5 towards the end of the century (e.g. ICPDR 2019; ICPDR/LMU 2018; Stagl and Hattermann 2016).

The review of case studies by ICPDR/LMU (2018) and Stolz et al. (2018) revealed additional general trends in water-related impacts of climate change in the DRB. Overall trends point to an increase in the frequency and intensity of extreme weather events such as dry spells, heat waves and heavy rainfall events, and thus droughts, low flows and floods (ICPDR 2019; 2021a; Stolz et al. 2018). In addition, water demand in water-using sectors such as in agriculture (e.g. for irrigation), industry and energy production is expected to increase due to the warming climate (ICPDR 2019; Stolz et al. 2018). Increasing drought occurrence and decreasing summer river discharges put agriculture at risk and reduce the availability of water for irrigation (ICPDR 2019). Where spatial or seasonal decreases in discharge and increasing extreme events are expected, negative impacts on hydropower production and navigation are also likely (ICPDR 2019; Stolz et al. 2018). Furthermore, decreasing summer discharges combined with increasing water temperatures could impair both thermal power production and aquatic ecosystems, which could be particularly the case in the Lower Danube (ICPDR 2019; Stolz et al. 2018).

However, the studies mentioned above are based on different methodologies and scenarios. Some projections are based on the older-generation Special Report on Emissions Scenarios (SRES) of IPCC AR3/4 (e.g. Stagl and Hattermann 2015) or on RCP scenarios by using either coarser global climate projections (e.g. Stagl and Hattermann 2016) or regional climate projections without clearly defined time horizons for a near- and long-term future (e.g. Bisselink et al. 2018a) (see also Probst and Mauser (2023) for an overview). Most of the case studies compiled by ICPDR/LMU (2018) and Stolz et al. (2018) cover only subsets of the DRB and are (naturally) not harmonized in terms of methodology, so that rather only qualitative statements on general trends can be made for the whole DRB (ICPDR 2019).

Therefore, systematic assessments of climate change impacts on surface water resources (e.g. precipitation, snow and soil water, discharge) for the entire DRB – using physically based LSPMs and state-of-the-art high-resolution regional climate projections – are still needed to provide robust quantitative estimates of possible futures of spatial and seasonal water availability in the near- and long-term future (Probst and Mauser 2023). This is also highly relevant for assessing whether future water availability can keep pace with possible irrigation developments.

1.6 Scope of the Thesis and Research Questions

The overarching objective of this thesis is to provide new scientific knowledge on water resources in the transboundary DRB between possible future trends in water demand and availability due to specific climatic and non-climatic factors. More specifically, this thesis aims to provide insights into upstream-downstream water competition in the WEFE nexus resulting from scenarios of large-scale agricultural irrigation in the DRB, and into the projected impacts of climate change on water resources in the DRB. All investigations are based on simulation studies using the physically based, hydro-agroecological LSPM

PROMET. For this, methodological aspects concerning the model setup and the meteorological forcings including their bias correction are also addressed in preparation for the application-oriented studies.

As described in Section 1.5, the DRB is a very interesting river basin for investigating the dynamics behind water demand and availability given its international character and pronounced natural and socio-economic heterogeneity. On the one hand, the DRB exhibits highly diverse spatial water availability due to its topography and its location in the transition zone between two climatic zones with a strong northwestern–southeastern precipitation gradient and contrasting precipitation projections. On the other hand, this is associated with different water use potentials (and possibly competing development strategies) in economic sectors such as agriculture and hydropower. As a result, water resources in the DRB may be subject to increasing climatic and non-climatic pressures in the future, which need to be better understood.

Section 1.4.1 outlined that physically based LSPMs are powerful tools for investigating water flows in river basins under current and changing boundary conditions, and that a hydro-agroecological coupling approach is beneficial as it explicitly takes into account the interactions between hydrological and vegetation processes. However, the pronounced heterogeneity and hydrological complexity of the DRB can make it challenging for an LSPM to accurately capture the ongoing physical processes in the basin. In this thesis, the physically based hydro-agroecological LSPM PROMET is applied for the first time to the entire DRB, which requires creating an appropriate PROMET model setup for the basin. This leads to the first research question:

> *RQ 1: Can the physically based LSPM PROMET be successfully applied for hydro-agroecological simulations under current and changing boundary conditions in the heterogeneous DRB? What are key requirements for the model setup?*

In addition to the LSPM and an appropriate model setup for the DRB, suitable meteorological forcing data are required. Section 1.4.2 outlined that global meteorological reanalysis data are widely used for driving LSPMs. However, Section 1.4.3 explained that the quality of precipitation forcing data is critical for reliable hydrological modelling – this is likely to be even more true for the topographically and hydrologically complex DRB – and that precipitation bias correction in particular is considered essential. It is also increasingly argued – at least in the context of climate change impact assessments – that observational uncertainty should be considered in the precipitation bias correction procedure (e.g. Gampe et al. 2019; Prein and Gobiet 2017). As this issue may also be relevant for historical reanalysis data, it appears reasonable to evaluate different precipitation reference datasets in terms of their suitability for bias correction of reanalysis data in the DRB. Since the aim of this thesis is to analyze water-related issues in the DRB by simulating water flows using a hydro-agroecological LSPM, it is important to assess how the different precipitation reference datasets for bias correction ultimately affect the quality of the (hydrological) simulations. This is similar to frequently used approaches in hydrological modelling studies, where precipitation forcings are indirectly evaluated by comparing modelled and observed discharge (e.g. Reis et al. 2022) (see Section 1.4.3). These considerations are at the core of the second research question:

RQ 2: Are global meteorological reanalysis data suitable to drive hydro-agroecological simulations in the hydrologically complex DRB, and what is the influence of bias correction using global to regional precipitation reference climatologies?

With the methodological foundation regarding model setup, meteorological forcing and bias correction in place, application-oriented research questions can be addressed. Section 1.5.1 gave a brief overview of the current agricultural situation in the DRB, which is far below its production potential in the Middle and Lower Danube. Given the ambitious national plans for large-scale expansion of agricultural irrigation there, water demand is very likely to increase. With limited water resources, this is likely to lead to increased upstream-downstream water competition and thus to trade-offs in the WEFE nexus, i.e. between agriculture, hydropower and aquatic ecosystems, all of which depend on the shared waters of the DRB. In this context, Dogaru et al. (2019) raised the question of whether the increased water demand resulting from the countries' irrigation plans can be met sustainably with the water resource availability in the basin and where hotspots of water scarcity will emerge. In addition, robust quantitative estimates of possible nexus trade-offs between agriculture, hydropower and aquatic ecosystems resulting from large-scale irrigation expansion are not yet available for the DRB. Furthermore, it is still unclear how irrigated cropland can be spatially allocated in an optimal and sustainable way within the DRB (see Section 1.5.2), and whether such land allocation considerations can even have positive side effects on ecosystems. Based on simulation studies of exemplary irrigation scenarios using PROMET, this research gap is addressed in the third research question:

RQ 3: What is the water demand for large-scale agricultural irrigation in the DRB, and what are the trade-offs in the WEFE nexus? Where are the limits of sustainability and potential hotspots of water scarcity? How can nexus trade-offs be mitigated and land be allocated to promote both efficient irrigation and ecosystem protection?

Moving on from non-climatic to climatic factors, Section 1.5.3 briefly outlined the state of the art on climate change impacts in the DRB. Water resources in the DRB are projected to be significantly affected by climate change, with precipitation trends described as wet regions and seasons becoming wetter and dry regions and seasons drier (ICPDR 2019). As a result, water resource availability in the DRB is projected to change both spatially and seasonally, with corresponding implications for water-using sectors. However, the considerable uncertainties, especially in the discharge projections, and the different methodologies of the case studies in the DRB impair the quantitative reliability of the available studies to date. This requires systematic and robust state-of-the-art estimates of climate change impacts on water resource availability (including precipitation, snow and soil water, discharge) in the entire DRB using a physically based LSPM and incorporating the latest high-resolution regional climate projections for the near and far future (see Section 1.5.3). Based on a climate change impact assessment using PROMET, this is addressed in the fourth research question:

RQ 4: What are the impacts of climate change on spatial and seasonal water resource availability in the DRB based on the latest regional climate projections? What are the implications for water-using sectors?

Based on the findings of the application-oriented research questions, a more comprehensive understanding of the possible future climatic and non-climatic challenges for water resources in the DRB can be gained, particularly as a consequence of the possible water demand for agricultural irrigation on the one hand, and the projected availability of water resources due to climate change on the other. The fifth research question therefore aims to integrate the findings of the third and fourth research questions:

RQ 5: Are water resources in the DRB likely to face increasing pressure in the future due to a possible expansion of agricultural irrigation and climate change, and if so, where are the hotspots? What are the implications for nexus trade-offs and mitigation options?

2 Framework of the Thesis and Publications

This thesis comprises three fully published scientific papers based on simulation studies using PROMET in the DRB and providing answers to the five research questions set out in Section 1.6. The papers involve a methodological evaluation of the PROMET setup and the meteorological forcings including their bias correction (paper I: Probst and Mauser (2022)), and two application studies: an assessment of water competition in the WEFE nexus under agricultural irrigation scenarios (paper II: Probst et al. (2024)) and an assessment of the climate change impacts on water resources (paper III: Probst and Mauser (2023)). Figure 2 provides an overview of the scope of the papers, the research questions they address and how they are integrated into the framework of this thesis.

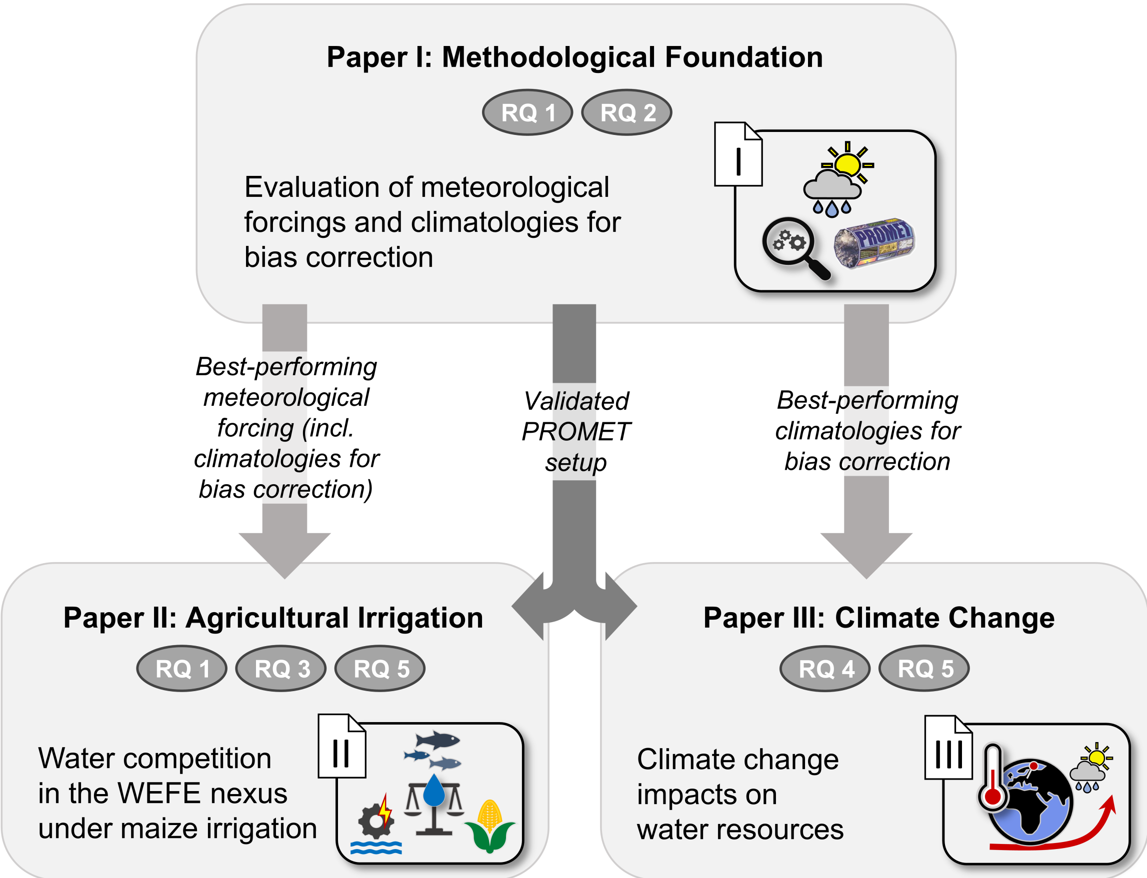

Figure 2: Schematic overview of the logical arrangement of the three papers within this thesis, indicating their scope and research questions (RQ) addressed in the Danube River Basin.

Paper I forms the methodological backbone within the framework of this thesis, upon which the application studies in paper II and III are founded. In paper I, the PROMET model setup for the DRB is established and validated in terms of river discharge at selected gauges. The PROMET setup consists, amongst others, of a comprehensive parameterization of relevant model parameters (e.g. vegetation, hydrology) and a LULC map with the spatial distribution of agricultural crops including their management (i.e. sowing dates, fertilization, cultivar selection) in the DRB. The capability of the physically based LSPM PROMET to carry out hydro-agroecological simulations in the heterogeneous DRB is assessed. The main objective of paper I is to evaluate (i) the performance of global meteorological forcing datasets (ERA5, WFDE5) for driving hydro-agroecological PROMET simulations in the DRB for the period 1980–2016 and (ii) the influence of different precipitation reference climatologies used for bias correction. For the latter, global as well as high-resolution Alpine precipitation climatologies are compared. The evaluation is based on how the different meteorological forcing datasets and the different precipitation reference climatologies for bias correction affect the quality of the hydro-agroecological simulations in the DRB, using hydrological model efficiency measures as the performance criterion. Paper I provides answers to the research questions RQ 1 and RQ 2.

Paper II builds on the methodological foundation of paper I by conducting a first application study using the validated PROMET model setup: an assessment of agricultural irrigation scenarios in the DRB. For this purpose, PROMET is driven with the best-performing meteorological forcing dataset (including bias correction with the best-performing reference climatologies) from paper I. In addition, maize yield and hydropower production are validated in paper II. The main objective of paper II is to quantify water competition between agriculture, hydropower and aquatic ecosystems (i.e. the trade-offs in the WEFE nexus) resulting from large-scale maize irrigation scenarios in the DRB for the period 2011–2020. The irrigation scenarios assume maize intensification associated with irrigation near rivers, with irrigation water being taken from the nearest river. Three maize scenarios are evaluated: (i) a rainfed scenario, (ii) an unsustainable irrigation scenario in which the EFRs of rivers are not respected when extracting irrigation water, and (iii) a sustainable irrigation scenario in which EFRs are maintained. In addition, the potential for land sparing as a result of increased maize productivity through irrigation is assessed. Paper II provides answers to the research questions RQ 1, RQ 3 and RQ 5.

Paper III builds on the methodological foundation of paper I by conducting a second application study using the validated PROMET model setup: an assessment of climate change impacts in the DRB. For this purpose, PROMET is driven with a high-resolution EURO-CORDEX EUR-11 GCM-RCM ensemble, which is bias-corrected with the best-performing reference climatologies from paper I. The main objective of paper III is to analyze the projected impacts of climate change on temperature, water resources (i.e. precipitation, soil water content, snow water equivalent, river discharge) and plant water stress in the DRB under the RCP2.6 and RCP8.5 emissions scenarios in the near (2031–2060) and far future (2071–2100) compared to the historical reference (1971–2000). Paper III provides answers to the research questions RQ 4 and RQ 5.

In the following, the abstracts of the three papers are given to outline their scope and core findings. The full papers are provided in the appendices (paper I: Appendix A; paper II: Appendix B.1 and B.2; paper III: Appendix C).

2.1 Paper I: Evaluation of ERA5 and WFDE5 Forcing Data for Hydrological Modelling and the Impact of Bias Correction With Regional Climatologies: A Case Study in the Danube River Basin

Abstract. *Study region:* The Danube River Basin.

Study focus: Hydrological modelling of large, heterogeneous watersheds requires appropriate meteorological forcing data. The global meteorological reanalysis ERA5 and the global forcing dataset WFDE5 were evaluated for driving an uncalibrated setup of the mechanistic hydrological model PROMET (0.00833333°/1 h resolution) for the period 1980–2016. Different climatologies were used for linear bias correction of ERA5: the global WorldClim 2 temperature and precipitation climatologies and the regional GLOWA and PRISM Alpine precipitation climatologies. Simulations driven with the uncorrected ERA5 reanalysis, the WFDE5 forcing dataset, ERA5 bias-corrected with WorldClim 2 and ERA5 bias-corrected with a GLOWA-PRISM-WorldClim 2 mosaic were evaluated regarding percent bias of discharge and model efficiency.

New hydrological insights for the region: Simulations yielded good model efficiencies and low percent biases of discharge at selected gauges. Uncalibrated model efficiencies corresponded with previous hydrological modelling studies. ERA5 and WFDE5 were well suited to drive PROMET in the hydrologically complex Danube basin, but bias correction of precipitation was essential for ERA5. The ERA5-driven simulation bias-corrected with a GLOWA-PRISM-WorldClim 2 mosaic performed best. Bias correction with GLOWA and PRISM outperformed WorldClim 2 in the Alps due to more realistic small-scale Alpine precipitation patterns resulting from higher station densities. In mountainous terrain, we emphasize the need for regional high-resolution precipitation climatologies and recommend them for bias correction of precipitation rather than global datasets.

This paper was published in Elsevier's *Journal of Hydrology: Regional Studies* (see Appendix A):

Probst, E. and Mauser, W. (2022): Evaluation of ERA5 and WFDE5 forcing data for hydrological modelling and the impact of bias correction with regional climatologies: A case study in the Danube River Basin. *Journal of Hydrology: Regional Studies*, 40: 101023. https://doi.org/10.1016/j.ejrh.2022.101023

2.2 Paper II: The Water-Energy-Food-Ecosystem Nexus in the Danube River Basin: Exploring Scenarios and Implications of Maize Irrigation

Abstract. The Water-Energy-Food-Ecosystem (WEFE) nexus concept postulates that water, energy production, agriculture and ecosystems are closely interlinked. In transboundary river basins, different sectors and countries compete for shared water resources. In the Danube River Basin (DRB), possible expansion of agricultural irrigation is expected to intensify water competition in the WEFE nexus, however, trade-offs have not yet been quantified. Here, we quantified trade-offs between agriculture, hydropower and (aquatic) ecosystems in the DRB resulting from maize irrigation when irrigation water was withdrawn from rivers. Using the process-based hydro-agroecological model PROMET, we simulated three maize scenarios for the period 2011–2020: (i) rainfed; (ii) irrigated near rivers without considering environmental flow requirements (EFRs); (iii) irrigated near rivers with water abstractions complying with EFRs. Maize yield and water use efficiency (WUE) increased by 101–125% and 29–34% under irrigation compared to rainfed cultivation. Irrigation water withdrawals from rivers resulted in moderate to severe discharge reductions and, without consideration of EFRs, to substantial EFR infringements. Annual hydropower production decreased by 1.0–1.9% due to discharge reductions. However, the financial turnover increase in agriculture (5.8–7.2 billion €/a) was two orders of magnitude larger than the financial turnover decrease in hydropower (23.9–47.8 million €/a), making water more profitable in agriculture. Irrigation WUE was highest for EFR-compliant irrigation, indicating that maintaining EFRs is economically beneficial and that improving WUE is key to attenuating nexus water competition. Current maize production could be met on the most productive 35–41% of current maize cropland under irrigation, allowing 59–65% to be returned to nature without loss of production. Maize priority areas were on fertile lowlands near major rivers, while biodiversity priority areas were on marginal cropland of highest biodiversity intactness. Our quantitative trade-off analysis can help identifying science-based pathways for sustainable WEFE nexus management in the DRB, also in light of climate change.

This paper was published in the Elsevier journal *Science of the Total Environment* (see Appendix B.1 and B.2):

Probst, E., Fader, M. and Mauser, W. (2024): The water-energy-food-ecosystem nexus in the Danube River Basin: Exploring scenarios and implications of maize irrigation. *Science of The Total Environment*, 914: 169405. https://doi.org/10.1016/j.scitotenv.2023.169405

2.3 Paper III: Climate Change Impacts on Water Resources in the Danube River Basin: A Hydrological Modelling Study Using EURO-CORDEX Climate Scenarios

Abstract. Climate change affects the hydrological cycle of river basins and strongly impacts water resource availability. The mechanistic hydrological model PROMET was driven with an ensemble of EURO-CORDEX regional climate model projections under the emission scenarios RCP2.6 and RCP8.5 to analyze changes in temperature, precipitation, soil water content, plant water stress, snow water equivalent (SWE) and runoff dynamics in the Danube River Basin (DRB) in the near (2031–2060) and far future (2071–2100) compared to the historical reference (1971–2000). Climate change impacts remain moderate for RCP2.6 and become severe for RCP8.5, exhibiting strong year-round warming trends in the far future with wetter winters in the Upper Danube and drier summers in the Lower Danube, leading to decreasing summer soil water contents, increasing plant water stress and decreasing SWE. Discharge seasonality of the Danube River shifts toward increasing winter runoff and decreasing summer runoff, while the risk of high flows increases along the entire Danube mainstream and the risk of low flows increases along the Lower Danube River. Our results reveal increasing climate change-induced discrepancies between water surplus and demand in space and time, likely leading to intensified upstream–downstream and inter-sectoral water competition in the DRB under climate change.

This paper was published in the MDPI journal *Water* (see Appendix C):

Probst, E. and Mauser, W. (2023): Climate Change Impacts on Water Resources in the Danube River Basin: A Hydrological Modelling Study Using EURO-CORDEX Climate Scenarios. *Water*, 15(1): 8. https://doi.org/10.3390/w15010008

3 Synthesis, Conclusions and Outlook

The overarching objective of this thesis is to provide new scientific knowledge on water resources in the transboundary DRB between the poles of demand and availability under the looming future challenges of agricultural irrigation and climate change. More specifically, this thesis assesses (i) upstream-downstream water competition in the WEFE nexus under scenarios of expanded agricultural irrigation and (ii) projected climate change impacts on water resources in the DRB. The physically based LSPM PROMET is used for hydro-agroecological simulation studies in the DRB, for which (iii) methodological evaluations of the model setup and the meteorological forcings including their bias correction are also carried out. In the following, the core findings and conclusions of the three scientific papers underlying this thesis are synthesized by answering the five research questions set out in Section 1.6. In this context, the main implications of the findings described are also given.

RQ 1: Can the physically based LSPM PROMET be successfully applied for hydro-agroecological simulations under current and changing boundary conditions in the heterogeneous DRB? What are key requirements for the model setup?

In this thesis, a setup of the physically based hydro-agroecological LSPM PROMET is established for the heterogeneous DRB and successfully validated in terms of discharge (paper I), maize yield and hydropower production (paper II). This demonstrates that the coupled, physically based land surface processes and their interactions (including human interventions) are represented in their correct spatiotemporal arrangement in the basin and proves the successful applicability of PROMET in the DRB. In this context, a key requirement for the PROMET setup is a physically consistent and plausibility-tested parameterization, as well as spatially explicit information on terrain, soil and LULC. The LULC map developed in paper I includes the spatial distribution of agricultural crops and their management in the DRB. This is essential for the realistic simulation of the crop-specific biophysical processes, which in their spatial distribution influence water balance and runoff generation (relevant in papers I, II and III) or agricultural yields and production volumes (e.g. of maize) (relevant in paper II).

Avoiding extensive empirical calibration of PROMET increases confidence in the model's spatial and temporal transferability and predictive power when simulating the effects of changing boundary conditions on water flows (Mauser and Bach 2009), which are at the core of the presented application studies, either due to the introduction of irrigation (paper II) or due to climate change (paper III). The transferability of PROMET makes it a powerful tool for assessing land use scenarios or climate change impacts, as subsequent simulation studies in both the DRB and other river basins can be carried out in a time- and cost-efficient manner.

RQ 2: Are global meteorological reanalysis data suitable to drive hydro-agroecological simulations in the hydrologically complex DRB, and what is the influence of bias correction using global to regional precipitation reference climatologies?

Paper I (Probst and Mauser 2022) shows that global meteorological reanalysis data are suitable to drive hydro-agroecological simulations in the hydrologically complex DRB, but require (i) bias correction and (ii) a critical site-specific selection of a suitable precipitation reference climatology. While the global climatology performs well in the Middle and Lower Danube (excl. Alps) when used for bias correction, the high-resolution Alpine climatologies clearly outperform the global climatology in the complex Alpine terrain, yielding best hydrological model efficiencies. The Alpine climatologies, based on higher station densities, show spatially redistributed, more heterogeneous and small-scale precipitation patterns – evidently better capturing Alpine precipitation features. Moreover, the added value of undercatch correction in mountainous terrain is apparent (WFDE5). This demonstrates the well-known benefits of high station density and undercatch correction to reduce common sources of uncertainty (e.g. data scarcity, undercatch) in observational precipitation datasets in mountainous terrain (e.g. Fick and Hijmans 2017; Prein and Gobiet 2017; Sevruk 2006). The findings also underline the need for careful site-specific selection of a suitable precipitation climatology for bias correction of reanalysis data under consideration of the observational uncertainty inherent in reference datasets (similar to related conclusions of, e.g. Gampe et al. (2019) on RCM bias correction). However, paper I goes a step further and shows the added value of the (Alpine) precipitation climatologies for bias correction by assessing their influence on the quality of hydrological modelling, thus indirectly validating the corresponding bias-corrected precipitation forcings via discharge and bypassing the issue of observational uncertainty when directly validating precipitation data (e.g. Reis et al. 2022). Overall, paper I clearly highlights the need for regional high-resolution precipitation climatologies based on high station density for bias correction of reanalysis data to adequately simulate the complex hydrological processes in Alpine terrain.

This conclusion is critical for any (hydrological) modelling studies in the DRB that generate information on water availability in rivers (as in papers II and III), since inaccuracies in the simulation of headwater catchments propagate downstream and influence the volume, dynamics and timing of runoff in the downstream sub-basins. Nevertheless, with appropriate climatologies at hand, the general applicability of global reanalysis data in the DRB greatly facilitates modelling efforts in data-scarce regions (e.g. the Middle and Lower Danube) where weather station time series are insufficient for direct meteorological input.

> *RQ 3: What is the water demand for large-scale agricultural irrigation in the DRB, and what are the trade-offs in the WEFE nexus? Where are the limits of sustainability and potential hotspots of water scarcity? How can nexus trade-offs be mitigated and land be allocated to promote both efficient irrigation and ecosystem protection?*

Paper II (Probst et al. 2024) shows that an exemplary scenario of large-scale irrigation of maize could realize large untapped yield potentials in the agricultural lowlands of the Middle and Lower Danube, but the irrigation water demand is considerable, rising in an upstream-downstream gradient. The extraction of irrigation water from rivers affects surface water resources by strongly reducing discharges in the Middle and Lower Danube, exacerbating upstream-downstream water competition and leading to trade-offs in the WEFE nexus. Meeting the full irrigation water demand for maize requires 12.9 billion m^3/a and results in a 125% yield increase, a 1.9% decrease in hydropower production and substantial violations of EFRs, threatening aquatic ecosystems. Sustainable irrigation (i.e. by maintaining EFRs) allows only half the water extraction, i.e. 6.5 billion m^3/a, but still results in a 101% yield increase – indicating a higher irrigation WUE in the sustainable case – and a 1.0% decrease in hydropower production. However, in large parts of the agricultural lowlands in the Middle and Lower Danube (i.e. the Pannonian Basin, the Romanian and Moldavian Plain) that are situated along tributaries instead of the Danube mainstream, the amount of sustainably extractable river water is often too low to meet the water demand of maize. This indicates hotspots of physical water scarcity and implies that the sustainable availability of blue water is a limiting factor for yield increases in these regions when rivers are the only source of irrigation water, providing initial answers to the questions of Dogaru et al. (2019).

Paper II also shows that the use of blue river water for irrigation generates more revenue in agriculture (several billion €/a) than is lost to hydropower (several tens of millions €/a). This suggests that economic considerations may favor agricultural irrigation expansion over hydropower. Strategies to maximize economic benefits of river water, following the UNECE (2016) idea of cumulative water values, could be to promote hydropower on rivers upstream (incl. technical efficiency improvements) and to promote sustainable irrigation (combined with hydropower) in the fertile lowlands downstream. This could also mean a certain upstream-downstream labor division among DRB countries in food and energy production.

A key finding of paper II is that irrigation WUE is optimized when (i) irrigation water is prioritized to maize sites with highest (water-limited) yield gaps, (ii) nearby river flows can meet irrigation water demand throughout the season, and (iii) irrigation is sustainable, which indicates also economic benefits of protecting aquatic ecosystems. This highlights that pairing efficient and sustainable irrigation is a win-win situation between economic and environmental interests and key to mitigating water competition and nexus trade-offs.

Paper II further shows that productivity gains from sustainable irrigation could spare more than half of the maize cropland for nature, with irrigation priority areas allocated on fertile cropland near major rivers and biodiversity priority areas allocated on marginal cropland with high biodiversity intactness. This ties the use of land resources to irrigation and points to large untapped potentials for more water-efficient land use, allowing for significant land sparing and thus also for the protection of terrestrial ecosystems. Coordinated strategies for integrated, resource-efficient and sustainable water and land resource management therefore offer opportunities to reconcile the protection of both terrestrial and aquatic ecosystems.

RQ 4: What are the impacts of climate change on spatial and seasonal water resource availability in the DRB based on the latest regional climate projections? What are the implications for water-using sectors?

Paper III (Probst and Mauser 2023) shows that the projected climate change impacts in the DRB are moderate under RCP2.6 and intensify under RCP8.5, especially in the far future. Under RCP8.5, water availability (i.e. areal precipitation and discharge at the DRB's outlet) is projected to increase slightly in the annual budget, but exhibits a clear spatial and seasonal redistribution. General RCP8.5 trends show increasing winter precipitation (+26.6% and +23.8% in near/far future) and winter discharge in the Upper Danube and decreasing summer precipitation (–6.5% and –12.6% in near/far future) and summer discharge in the Lower Danube, reinforcing the northwest–southeast gradient of decreasing water availability. Under both RCP2.6 and RCP8.5, the role of snowmelt as a water resource declines, leading to alterations of river regimes. The general RCP8.5 trends in water availability of paper III are largely consistent with those outlined by ICPDR (2019), while RCP2.6 trends show rather increasing water availability in most seasons, especially in the far future.

Paper III also shows that hotter and partly drier summers, projected especially in the Middle and Lower Danube lowlands, lead to decreasing soil moisture (strong for RCP8.5; weaker for RCP2.6), and exacerbate water stress during the growing season of summer crops. This is likely to increase pressure to expand agricultural irrigation and amplify irrigation water demand, while rising temperatures may extend the growing season. However, the RCP8.5 trend of decreasing summer discharge in the Lower Danube is likely to reduce the amount of river water available for irrigation, possibly hampering agriculture. Moreover, the RCP8.5 trends in seasonal discharge (increase in winter, decrease in summer) may shift hydropower potential from summer to winter, which could possibly offset summer losses. In addition, the trends towards more frequent high flows on the entire Danube mainstream (RCP2.6 and RCP8.5) and more frequent low flows on the Middle and Lower Danube River (RCP8.5, far future) point to an increasingly uneven and erratic water availability in rivers. This is likely to pose additional challenges for agricultural irrigation, energy production and river navigability, and may threaten aquatic ecosystems. Overall, the very general tendencies of water-related impacts under RCP8.5 are largely in line with the general trends outlined by ICPDR (2019), ICPDR/LMU (2018) and Stolz et al. (2018).

The findings of paper III imply that future water availability and the associated impacts on water-using sectors in the DRB will strongly depend on whether future climate tends to follow the RCP2.6 or the RCP8.5 pathway. This makes the DRB's water future highly dependent on the success of global efforts to meet the 2 °C goal of the Paris Agreement.

> *RQ 5: Are water resources in the DRB likely to face increasing pressure in the future due to a possible expansion of agricultural irrigation and climate change, and if so, where are the hotspots? What are the implications for nexus trade-offs and mitigation options?*

Integrating the findings of paper II (Probst et al. 2024) and paper III (Probst and Mauser 2023), water resources in the DRB are likely to face increasing pressure in the future as a result of (i) a possible expansion of agricultural irrigation with its associated (also climate-dependent) water demand, and (ii) climate change with the projected spatial and seasonal changes in water availability. A numerical comparison of climatic and non-climatic impacts on the summer water balance of the DRB is interesting. The mean summer discharge (JJA) at the DRB outlet is projected to change by +5.1% and +9.5% (RCP2.6 in the near/far future), and by –1.5% and –2.9% (RCP8.5 in the near/far future) due to climate change (paper III), and changes by –11.3% and –22.6% (assuming sustainable/unsustainable irrigation) due to the agricultural irrigation scenarios (paper II). The latter numbers are a rough estimate and calculated by dividing mean seasonal irrigation water volume [m^3] by mean summer runoff volume [m^3] (JJA) in 2011–2020. This comparison is not realistic due to the extreme irrigation scenarios, but shows that the potential impact of irrigation on the DRB's summer water balance can be of considerable magnitude compared to the impact of climate change.

Potential hotspots of water resources facing increasing pressure in the future are likely to emerge particularly in the agricultural lowlands on the Danube tributaries in the Middle Danube (i.e. the eastern Pannonian Basin) and the Lower Danube (i.e. the Romanian and Moldavian Plain). Several factors coincide here: First, soil water deficits, resulting water stress and irrigation water demand (for maize) are already high under current climate (paper II) and are projected to further increase under climate change due to increasing temperature-driven saturation deficits (RCP2.6 and RCP8.5; paper III) and decreasing precipitation (RCP8.5; paper III) in the growing season. Second, the amount of sustainably extractable river water is already limited under current climate (paper II) and is likely to further decrease due to the projected decrease in summer discharge of the tributaries (RCP8.5; paper III).

Overall, the trends outlined indicate an increasing spatial and seasonal discrepancy between water demand – driven by agricultural irrigation – and water availability – driven by climate change – in the DRB. This demand-availability mismatch in space and time is at the heart of physical water scarcity (e.g. Mekonnen and Hoekstra 2016). The future magnitude of this mismatch will be determined by future trends in agriculture and climate change, and is likely to culminate if the ambitious irrigation plans of the downstream DRB countries are realized and coincide with a future climate following the RCP8.5 pathway. As a result, upstream-downstream water competition in the WEFE nexus is likely to aggravate under climate change, with likely adverse effects on food and energy production and ecosystem integrity in the basin. Consequently, sustainable and (spatially) efficient irrigation will take on new urgency as a key strategy to mitigate pressure on water resources and nexus trade-offs.

Outlook

The anticipated trends in water demand and availability in the DRB create a nexus issue par excellence, posing major challenges for water-using economic sectors such as agriculture and the energy sector, as well as for natural ecosystems. With 20 countries relying on shared water resources in the DRB, challenges of this complexity transcend the national action level and require joint international commitment. The findings of this thesis can support science-based, integrated, transboundary, cross-sectoral and climate-resilient water resources and nexus management that (i) promotes efficient and sustainable water resource allocation and use as well as water-efficient land use, and (ii) aims to reconcile water, food and energy security and ecosystem integrity in the DRB also under a changing climate. The findings can also feed into novel concepts of irrigation management, such as the one proposed by Dogaru et al. (2019), which moves from a mere technical grasp of irrigation systems to a river basin approach aiming to spatially optimize irrigation and balance water demand and availability. International organizations such as the ICPDR can provide a platform for stakeholder dialogue to create synergies and minimize nexus trade-offs between water-using sectors and the environment, while harmonizing environmental standards (e.g. EFRs) and implementing tailored climate change adaptation measures. At this action level, transboundary and cross-sectoral cooperation could stimulate upstream-downstream benefit-sharing strategies for a spatially optimized water and land resource use throughout the basin. Overall, the findings of this thesis highlight the urgent need to integrate (quantitative) water allocation issues on an equal footing with qualitative aspects in water resource management in the DRB.

The results of this thesis provide many entry points for future research. Further studies could develop intelligent hydro-agricultural monitoring and forecasting systems that assimilate weather forecast and remote sensing data into LSPMs to provide recommendations on irrigation and river water extraction based on near real-time crop water status and river runoff. Future research could evaluate water-optimized and climate-resilient crop allocation with respect to water availability or assess combined sources of irrigation water (e.g. rivers, groundwater, reservoirs, rainwater harvesting) for the potential to reduce nexus trade-offs or create synergies (e.g. between irrigation and reservoir hydropower). Further studies should also assess actual irrigation plans as soon as more detailed information is available, to fully address the question of Dogaru et al. (2019) of whether water availability can sustainably meet irrigation water needs and where water scarcity hotspots will emerge. As climate change will likely alter the upstream-downstream baseline conditions in the WEFE nexus in the DRB, an explicit climate-water-energy-food-ecosystem nexus research framework is needed to thoroughly understand the nexus-climate interactions and to assess the climate change impacts on the water availability-demand relation, as Dogaru et al. (2019) suggested.

From a conceptual perspective, this thesis shows that process based hydro-agroecological LSPMs are beneficial for assessing water-related nexus and climate change issues in river basins. Moving forward, the use of state-of-the-art reanalyses or climate projections is advisable to benefit from advances in reanalysis schemes or climate model development that could eventually eliminate the need for bias correction and reduce uncertainties in climate change impact research, thus facilitating the formulation of up-to-date adaptation measures. Overall, the novel methods and applications presented in this thesis can well serve as good practice examples transferable to other river basins. Innovative approaches in integrated river basin research are vital to promote a thorough understanding of how to ensure efficient, sustainable and climate-resilient use of finite water and land resources in the face of current and future challenges, not only in the DRB but also in other river basins around the world.

References

Abbott, B.W., Bishop, K., Zarnetske, J.P., Minaudo, C., Chapin, F.S., Krause, S., Hannah, D.M., Conner, L., Ellison, D., Godsey, S.E., Plont, S., Marçais, J., Kolbe, T., Huebner, A., Frei, R.J., Hampton, T., Gu, S., Buhman, M., Sara Sayedi, S., Ursache, O., Chapin, M., Henderson, K.D. and Pinay, G. (2019): Human domination of the global water cycle absent from depictions and perceptions. *Nature Geoscience*, 12(7): 533-540. https://doi.org/10.1038/s41561-019-0374-y

Adam, D. (2023): What a 190-year-old equation says about rainstorms in a changing climate. *Proceedings of the National Academy of Sciences*, 120(14): e2304077120. https://doi.org/10.1073/pnas.2304077120

Addor, N. and Fischer, E.M. (2015): The influence of natural variability and interpolation errors on bias characterization in RCM simulations. *Journal of Geophysical Research: Atmospheres*, 120(19): 10,180-10,195. https://doi.org/10.1002/2014JD022824

Babkin, V.I. and Vuglinsky, V.S. (2004): Physical Geography. In: Shiklomanov, I.A. and Rodda, J.C. (Eds.): World Water Resources at the Beginning of the Twenty-First Century. Cambridge University Press, Cambridge, United Kingdom, pp. 1-9.

Ball, J.T., Woodrow, I.E. and Berry, J.A. (1987): A model predicting stomatal conductance and its contribution to the control of photosynthesis under different environmental conditions. In: Biggins, J. (Ed.): Progress in photosynthesis research. Springer Science+Business Media, Dordrecht, pp. 221-224. https://doi.org/10.1007/978-94-017-0519-6_48

Baranyai, G. (2015): Transboundary water cooperation in the European Union: a hydro-political gap assessment. Danube Region strategy. Water Quality Priority Area (PA4), Hungary. https://waterquality.danube-region.eu/wp-content/uploads/sites/13/sites/13/2019/09/BG_Transboundary_Water_Cooperation_CONF_BY_DANUBE_STRAT.pdf

Baranyai, G. (2020a): The Resilience of Transboundary Water Governance Within the European Union: A Legal and Institutional Analysis. In: Baranyai, G. (Ed.): European Water Law and Hydropolitics: An Inquiry into the Resilience of Transboundary Water Governance in the European Union. Springer International Publishing, Cham, pp. 119-168. https://doi.org/10.1007/978-3-030-22541-4_10

Baranyai, G. (2020b): Transboundary Water Governance in the European Union. In: Baranyai, G. (Ed.): European Water Law and Hydropolitics: An Inquiry into the Resilience of Transboundary Water Governance in the European Union. Springer International Publishing, Cham, pp. 79-112. https://doi.org/10.1007/978-3-030-22541-4_8

Betts, R.A., Boucher, O., Collins, M., Cox, P.M., Falloon, P.D., Gedney, N., Hemming, D.L., Huntingford, C., Jones, C.D., Sexton, D.M.H. and Webb, M.J. (2007): Projected increase in continental runoff due to plant responses to increasing carbon dioxide. *Nature*, 448(7157): 1037-1041. https://doi.org/10.1038/nature06045

Bisselink, B., Bernhard, J., Gelati, E., Jacobs, C., Adamovic, M., Mentaschi, L., Lavalle, C. and de Roo, A. (2018a): Impact of a changing climate, land use, and water usage on water resources in the Danube river basin. A model simulation study. EUR 29228 EN, JRC111817, Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/561327

Bisselink, B., Roo, A.d., Bernhard, J. and Gelati, E. (2018b): Future projections of water scarcity in the Danube River Basin due to land use, water demand and climate change. *Journal of Environmental Geography*, 11(3/4): 25-36. https://doi.org/10.2478/jengeo-2018-0010

Brienen, S., Früh, B., Walter, A., Trusilova, K. and Becker, P. (2016): A Central European precipitation climatology – Part II: Application of the high-resolution HYRAS data for COSMO-CLM evaluation. *Meteorologische Zeitschrift*, 25(2): 195-214. https://doi.org/10.1127/metz/2016/0617

Burek, P., Satoh, Y., Fischer, G., Kahil, M.T., Scherzer, A., Tramberend, S., Nava, L.F., Wada, Y., Eisner, S., Flörke, M., Hanasaki, N., Magnuszewski, P., Cosgrove, B. and Wiberg, D. (2016): Water Futures and Solution: Fast Track Initiative (Final Report). IIASA Working Paper. International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria. https://pure.iiasa.ac.at/id/eprint/13008/

Caretta, M.A., Mukherji, A., Arfanuzzaman, M., Betts, R.A., Gelfan, A., Hirabayashi, Y., Lissner, T.K., Liu, J., Lopez Gunn, E., Morgan, R., Mwanga, S. and Supratid, S. (2022): Water. In: Pörtner, H.-O., Roberts, D.C., Tignor, M., Poloczanska, E.S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A. and Rama, B. (Eds.): Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 551-712. https://doi.org/10.1017/9781009325844.006

Carmona-Moreno, C., Dondeynaz, C. and Biedler, M. (2019): Position Paper on Water, Energy, Food, and Ecosystem (WEFE) Nexus and Sustainable Development Goals (SDGs). EUR 29509 EN, JRC114177, Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/5295

Carvalho, L., Mackay, E.B., Cardoso, A.C., Baattrup-Pedersen, A., Birk, S., Blackstock, K.L., Borics, G., Borja, A., Feld, C.K., Ferreira, M.T., Globevnik, L., Grizzetti, B., Hendry, S., Hering, D., Kelly, M., Langaas, S., Meissner, K., Panagopoulos, Y., Penning, E., Rouillard, J., Sabater, S., Schmedtje, U., Spears, B.M., Venohr, M., van de Bund, W.

and Solheim, A.L. (2019): Protecting and restoring Europe's waters: An analysis of the future development needs of the Water Framework Directive. *Science of the Total Environment*, 658: 1228-1238. https://doi.org/10.1016/j.scitotenv.2018.12.255

Cetin, K. and Mauser, W. (2023): The Role of Recent Climate Change in Explaining the Statistical Yield Increase of Maize in Northern Bavaria—A Model Study. *Agriculture*, 13(7): 1370. https://doi.org/10.3390/agriculture13071370

Chen, D.-X., Coughenour, M.B., Knapp, A.K. and Owensby, C.E. (1994): Mathematical simulation of C_4 grass photosynthesis in ambient and elevated CO_2. *Ecological Modelling*, 73(1): 63-80. https://doi.org/10.1016/0304-3800(94)90098-1

Chiarelli, D.D., D'Odorico, P., Müller, M.F., Mueller, N.D., Davis, K.F., Dell'Angelo, J., Penny, G. and Rulli, M.C. (2022): Competition for water induced by transnational land acquisitions for agriculture. *Nature Communications*, 13(1): 505. https://doi.org/10.1038/s41467-022-28077-2

Cornes, R.C., van der Schrier, G., van den Besselaar, E.J.M. and Jones, P.D. (2018): An Ensemble Version of the E-OBS Temperature and Precipitation Data Sets. *Journal of Geophysical Research: Atmospheres*, 123(17): 9391-9409. https://doi.org/10.1029/2017JD028200

Cucchi, M., Weedon, G.P., Amici, A., Bellouin, N., Lange, S., Müller Schmied, H., Hersbach, H. and Buontempo, C. (2020): WFDE5: bias-adjusted ERA5 reanalysis data for impact studies. *Earth System Science Data*, 12(3): 2097-2120. https://doi.org/10.5194/essd-12-2097-2020

Cunge, J.A. (1969): On The Subject Of A Flood Propagation Computation Method (Muskingum Method). *Journal of Hydraulic Research*, 7(2): 205-230. https://doi.org/10.1080/00221686909500264

D'Odorico, P., Davis, K.F., Rosa, L., Carr, J.A., Chiarelli, D., Dell'Angelo, J., Gephart, J., MacDonald, G.K., Seekell, D.A., Suweis, S. and Rulli, M.C. (2018): The Global Food-Energy-Water Nexus. *Reviews of Geophysics*, 56(3): 456-531. https://doi.org/10.1029/2017RG000591

DDD (2018): Romania's Sustainable Development Strategy 2030. Departamentul pentru Dezvoltare Durabilă (DDD), Guvernul României, Bucharest. http://dezvoltaredurabila.gov.ro/web/wp-content/uploads/2019/03/Romanias-Sustainable-Development-Strategy-2030.pdf

De Roo, A., Bisselink, B., Beck, H., Bernhard, J., Burek, P., Reynaud, A., Pastori, M., Lavalle, C., Jacobs-Crisioni, C., Baranzelli, C., Zajac, Z. and Dosio, A. (2016): Modelling water demand and availability scenarios for current and future land use and climate in the Sava River Basin. Addressing the water-food-energy-ecosystem nexus. EUR 27701 EN, JRC99886, Publications Office of the European Union, Luxembourg. https://data.europa.eu/doi/10.2788/52758

Dee, D.P., Uppala, S.M., Simmons, A.J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M.A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A.C.M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A.J., Haimberger, L., Healy, S.B., Hersbach, H., Hólm, E.V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., McNally, A.P., Monge-Sanz, B.M., Morcrette, J.-J., Park, B.-K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J.-N. and Vitart, F. (2011): The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, 137(656): 553-597. https://doi.org/10.1002/qj.828

Denton, F., Halsnæs, K., Akimoto, K., Burch, S., Diaz Morejon, C., Farias, F., Jupesta, J., Shareef, A., Schweizer-Ries, P., Teng, F. and Zusman, E. (2022): Accelerating the transition in the context of sustainable development. In: Shukla, P.R., Skea, J., Slade, R., Al Khourdajie, A., van Diemen, R., McCollum, D., Pathak, M., Some, S., Vyas, P., Fradera, R., Belkacemi, M., Hasija, A., Lisboa, G., Luz, S. and Malley, J. (Eds.): Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1727-1790. https://doi.org/10.1017/9781009157926.019

Di Sante, F., Coppola, E. and Giorgi, F. (2021): Projections of river floods in Europe using EURO-CORDEX, CMIP5 and CMIP6 simulations. *International Journal of Climatology*, 41(5): 3203-3221. https://doi.org/10.1002/joc.7014

Doblas-Reyes, F.J., Sörensson, A.A., Almazroui, M., Dosio, A., Gutowski, W.J., Haarsma, R., Hamdi, R., Hewitson, B., Kwon, W.-T., Lamptey, B.L., Maraun, D., Stephenson, T.S., Takayabu, I., Terray, L., Turner, A. and Zuo, Z. (2021): Linking Global to Regional Climate Change. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R. and Zhou, B. (Eds.): Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1363-1512. https://doi.org/10.1017/9781009157896.012

Dogaru, D., Mauser, W., Balteanu, D., Krimly, T., Lippert, C., Sima, M., Szolgay, J., Kohnova, S., Hanel, M., Nikolova, M., Szalai, S. and Frank, A. (2019): Irrigation Water Use in the Danube Basin: Facts, Governance and Approach to Sustainability. *Journal of Environmental Geography*, 12(3-4): 1-12. https://doi.org/10.2478/jengeo-2019-0007

Douville, H., Raghavan, K., Renwick, J., Allan, R.P., Arias, P.A., Barlow, M., Cerezo-Mota, R., Cherchi, A., Gan, T.Y., Gergis, J., Jiang, D., Khan, A., Pokam Mba, W., Rosenfeld, D., Tierney, J. and Zolina, O. (2021): Water Cycle Changes. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R. and Zhou, B. (Eds.): Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1055-1210. https://doi.org/10.1017/9781009157896.010

EC (2000): Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. Official Journal of the European Communities, European Commission, Brussels. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32000L0060

EC and JRC (2019): JRC Hydro-power database. European Commission (EC), Joint Research Centre (JRC). http://data.europa.eu/89h/52b00441-d3e0-44e0-8281-fda86a63546d (last access: 12 February 2024)

Ehret, U., Zehe, E., Wulfmeyer, V., Warrach-Sagi, K. and Liebert, J. (2012): HESS Opinions "Should we apply bias correction to global and regional climate model data?". *Hydrology and Earth System Sciences*, 16(9): 3391-3404. https://doi.org/10.5194/hess-16-3391-2012

EUROSTAT (2023): Crops by classes of utilised agricultural area in number of farms and hectare by NUTS 2 regions (ef_lus_allcrops). https://ec.europa.eu/eurostat/web/agriculture/data/database (last access: 22 November 2023)

Eyring, V., Bony, S., Meehl, G.A., Senior, C.A., Stevens, B., Stouffer, R.J. and Taylor, K.E. (2016): Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development*, 9(5): 1937-1958. https://doi.org/10.5194/gmd-9-1937-2016

Fader, M., Cranmer, C., Lawford, R. and Engel-Cox, J. (2018): Toward an Understanding of Synergies and Trade-Offs Between Water, Energy, and Food SDG Targets. *Frontiers in Environmental Science*, 6(112). https://doi.org/10.3389/fenvs.2018.00112

Falkenmark, M. and Rockström, J. (2006): The New Blue and Green Water Paradigm: Breaking New Ground for Water Resources Planning and Management. *Journal of Water Resources Planning and Management*, 132(3): 129-132. https://doi.org/10.1061/(ASCE)0733-9496(2006)132:3(129)

FAO (2012): Coping with water scarcity. An action framework for agriculture and food security. FAO Water Reports. Food and Agriculture Organization of the United Nations (FAO), Rome. https://www.fao.org/3/i3015e/i3015e.pdf

FAO (2014): The Water-Energy-Food Nexus. A new approach in support of food security and sustainable agriculture. Food and Agriculture Organization of the United Nations (FAO), Rome. https://www.fao.org/documents/card/en/c/182bf36b-87fa-4ea5-b898-06c89c88f241/

FAO/IWMI (2018): More People, More Food… Worse Water? A Global Review of Water Pollution from Agriculture. Food and Agriculture Organization of the United Nations (FAO), International Water Management Institute (IWMI), Rome. www.fao.org/documents/card/en/c/CA0146EN/

Farquhar, G.D., von Caemmerer, S. and Berry, J.A. (1980): A biochemical model of photosynthetic CO_2 assimilation in leaves of C_3 species. *Planta*, 149(1): 78-90. https://doi.org/10.1007/bf00386231

Farr, T.G., Rosen, P.A., Caro, E., Crippen, R., Duren, R., Hensley, S., Kobrick, M., Paller, M., Rodriguez, E., Roth, L., Seal, D., Shaffer, S., Shimada, J., Umland, J., Werner, M., Oskin, M., Burbank, D. and Alsdorf, D. (2007): The Shuttle Radar Topography Mission. *Reviews of Geophysics*, 45(2): 1-33. https://doi.org/doi:10.1029/2005RG000183

Feher, J. and Muerth, M. (2015): Water models and scenarios inventory for the Danube region. Support to the Danube Water Nexus. EUR 27357 EN, JRC96545, Publications Office of the European Union, Luxembourg. https://doi.org/10.2788/412928

Feldbacher, E., Paun, M., Reckendorfer, W., Sidoroff, M., Stanica, A., Strimbu, B., Tusa, I., Vulturescu, V. and Hein, T. (2016): Twenty years of research on water management issues in the Danube Macro-region — past developments and future directions. *Science of The Total Environment*, 572: 1297-1306. https://doi.org/10.1016/j.scitotenv.2015.12.133

Fick, S.E. and Hijmans, R.J. (2017): WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. *International Journal of Climatology*, 37(12): 4302-4315. https://doi.org/10.1002/joc.5086

Flato, G., Marotzke, J., Abiodun, B., Braconnot, P., Chou, S.C., Collins, W., Cox, P., Driouech, F., Emori, S., Eyring, V., Forest, C., Gleckler, P., Guilyardi, E., Jakob, C., Kattsov, V., Reason, C. and Rummukainen, M. (2013): Evaluation of Climate Models. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P.M. (Eds.): Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 741-866. https://doi.org/10.1017/CBO9781107415324.020

Frei, C. and Schär, C. (1998): A precipitation climatology of the Alps from high-resolution rain-gauge observations. *International Journal of Climatology*, 18(8): 873-900. https://doi.org/10.1002/(SICI)1097-0088(19980630)18:8<873::AID-JOC255>3.0.CO;2-9

Früh, B., Schipper, H., Pfeiffer, A. and Wirth, V. (2006): A pragmatic approach for downscaling precipitation in alpine-scale complex terrain. *Meteorologische Zeitschrift*, 15(6): 631-646. https://doi.org/10.1127/0941-2948/2006/0137

Gampe, D. and Ludwig, R. (2017): Evaluation of Gridded Precipitation Data Products for Hydrological Applications in Complex Topography. *Hydrology*, 4(4): 53. https://doi.org/10.3390/hydrology4040053

Gampe, D., Schmid, J. and Ludwig, R. (2019): Impact of Reference Dataset Selection on RCM Evaluation, Bias Correction, and Resulting Climate Change Signals of Precipitation. *Journal of Hydrometeorology*, 20(9): 1813-1828. https://doi.org/10.1175/JHM-D-18-0108.1

Garnett, T., Appleby, M.C., Balmford, A., Bateman, I.J., Benton, T.G., Bloomer, P., Burlingame, B., Dawkins, M., Dolan, L., Fraser, D., Herrero, M., Hoffmann, I., Smith, P., Thornton, P.K., Toulmin, C., Vermeulen, S.J. and Godfray, H.C.J. (2013): Sustainable Intensification in Agriculture: Premises and Policies. *Science*, 341(6141): 33-34. https://doi.org/10.1126/science.1234485

Gentine, P., Green, J.K., Guérin, M., Humphrey, V., Seneviratne, S.I., Zhang, Y. and Zhou, S. (2019): Coupling between the terrestrial carbon and water cycles—a review. *Environmental Research Letters*, 14(8): 083003. https://doi.org/10.1088/1748-9326/ab22d6

GEO, Google, KTH, Enipedia and WRI (2018): Global Power Plant Database v1.3.0. Global Energy Observatory (GEO), Google, KTH Royal Institute of Technology in Stockholm, Enipedia, World Resources Institute (WRI), Published on Resource Watch and Google Earth Engine; http://resourcewatch.org/ https://earthengine.google.com/. https://datasets.wri.org/dataset/globalpowerplantdatabase (last access: 12 February 2024)

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M. and Toulmin, C. (2010): Food Security: The Challenge of Feeding 9 Billion People. *Science*, 327(5967): 812-818. https://doi.org/10.1126/science.1185383

Grambow, M. (2013): Bestandsaufnahme. In: Grambow, M. (Ed.): Nachhaltige Wasserbewirtschaftung: Konzept und Umsetzung eines vernünftigen Umgangs mit dem

Gemeingut Wasser. Vieweg+Teubner Verlag, Wiesbaden, pp. 1-35. https://doi.org/10.1007/978-3-8348-2275-8_1

Gutiérrez, J.M., Jones, R.G., Narisma, G.T., Alves, L.M., Amjad, M., Gorodetskaya, I.V., Grose, M., Klutse, N.A.B., Krakovska, S., Li, J., Martínez-Castro, D., Mearns, L.O., Mernild, S.H., Ngo-Duc, T., van den Hurk, B. and Yoon, J.-H. (2021): Atlas. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R. and Zhou, B. (Eds.): Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. https://doi.org/10.1017/9781009157896.021

GWP (2000): Integrated Water Resources Management. TAC Background Papers No. 4, Global Water Partnership (GWP), Technical Advisory Committee (TAC), Stockholm. https://www.gwp.org/globalassets/global/toolbox/publications/background-papers/04-integrated-water-resources-management-2000-english.pdf

Hank, T.B. (2008): A Biophysically Based Coupled Model Approach For the Assessment of Canopy Processes Under Climate Change Conditions. Dissertation, Faculty of Geosciences, Ludwig-Maximilians-Universität München. https://www.doi.org/10.5282/edoc.8725

Hank, T.B., Bach, H. and Mauser, W. (2015): Using a Remote Sensing-Supported Hydro-Agroecological Model for Field-Scale Simulation of Heterogeneous Crop Growth and Yield: Application for Wheat in Central Europe. *Remote Sensing*, 7(4): 3934-3965. https://doi.org/10.3390/rs70403934

Haslinger, K., Anders, I. and Hofstätter, M. (2013): Regional climate modelling over complex terrain: an evaluation study of COSMO-CLM hindcast model runs for the Greater Alpine Region. *Climate Dynamics*, 40(1): 511-529. https://doi.org/10.1007/s00382-012-1452-7

Hausfather, Z. and Peters, G.P. (2020): RCP8.5 is a problematic scenario for near-term emissions. *Proceedings of the National Academy of Sciences*, 117(45): 27791-27792. https://doi.org/10.1073/pnas.2017124117

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., De Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R.J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., de Rosnay, P., Rozum, I., Vamborg, F., Villaume, S. and Thépaut, J.-N. (2020): The ERA5 global reanalysis. *Quarterly Journal* *of the Royal Meteorological Society*, 146(730): 1999-2049. https://doi.org/10.1002/qj.3803

Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G. and Jarvis, A. (2005): Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology*, 25(15): 1965-1978. https://doi.org/doi:10.1002/joc.1276

Hoff, H. (2011): Understanding the Nexus. Background Paper for the Bonn2011 Conference: The Water, Energy and Food Security Nexus. Stockholm Environment Institute, Stockholm. https://www.sei.org/publications/understanding-the-nexus/

Hogeboom, R.J., de Bruin, D., Schyns, J.F., Krol, Maarten S. and Hoekstra, A.Y. (2020): Capping Human Water Footprints in the World's River Basins. *Earth's Future*, 8(2): e2019EF001363. https://doi.org/10.1029/2019EF001363

Huang, Z., Hejazi, M., Tang, Q., Vernon, C.R., Liu, Y., Chen, M. and Calvin, K. (2019): Global agricultural green and blue water consumption under future climate and land use changes. *Journal of Hydrology*, 574: 242-256. https://doi.org/10.1016/j.jhydrol.2019.04.046

ICPDR (1998): Convention on Cooperation for the Protection and Sustainable use of the Danube River (Danube River Protection Convention). International Commission for the Protection of the Danube River (ICPDR), Vienna, Austria. https://www.icpdr.org/sites/default/files/DRPC%20English%20ver.pdf

ICPDR (2005): The Danube River Basin District. Part A – Basin-wide overview. International Commission for the Protection of the Danube River (ICPDR), Vienna, Austria. https://www.icpdr.org/sites/default/files/ICPDR_gesamt_klein.pdf

ICPDR (2009): Danube River Basin District Management Plan. Part A – Basin-wide overview. International Commission for the Protection of the Danube River (ICPDR), Vienna, Austria. https://www.icpdr.org/tasks-topics/tasks/river-basin-management/danube-river-basin-management-plan-2009

ICPDR (2011): The Danube River Basin. Facts and Figures. International Commission for the Protection of the Danube River (ICPDR), Vienna, Austria. https://www.icpdr.org/sites/default/files/nodes/documents/icpdr_facts_figures.pdf

ICPDR (2013a): Assessment Report on Hydropower Generation in the Danube Basin. International Commission for the Protection of the Danube River (ICPDR), Vienna, Austria. https://www.icpdr.org/sites/default/files/nodes/documents/hydropower_assessment_report_danube_basin_-_final.pdf

ICPDR (2013b): Sustainable Hydropower Development in the Danube Basin. Guiding Principles. International Commission for the Protection of the Danube River (ICPDR), Vienna, Austria. https://www.icpdr.org/sites/default/files/nodes/documents/icpdr_hydropower_final.pdf

ICPDR (2014): The flow of Danube cooperation: a history of shared responsibility. Danube Watch 1/2014. International Commission for the Protection of the Danube River (ICPDR), Vienna, Austria. https://www.icpdr.org/publications/flow-danube-cooperation-history-shared-responsibility

ICPDR (2015): The Danube River Basin District Management Plan. Part A – Basin-wide overview. Update 2015. International Commission for the Protection of the Danube River (ICPDR), Vienna, Austria. https://www.icpdr.org/sites/default/files/nodes/documents/drbmp-update2015.pdf

ICPDR (2019): Climate Change Adaptation Strategy. International Commission for the Protection of the Danube River (ICPDR), Vienna, Austria. https://www.icpdr.org/sites/default/files/nodes/documents/icpdr_climate_change_adaptation_strategy_web.pdf

ICPDR (2021a): Danube River Basin Management Plan. Update 2021. International Commission for the Protection of the Danube River (ICPDR), Vienna, Austria. https://www.icpdr.org/tasks-topics/tasks/river-basin-management/danube-river-basin-management-plan-2021

ICPDR (2021b): Guidance Document on Sustainable Agriculture in the Danube River Basin. International Commission for the Protection of the Danube River (ICPDR), Vienna, Austria. https://www.icpdr.org/sites/default/files/nodes/documents/icpdr_guidance_document_on_sustainable_agriculture.pdf

ICPDR (2021c): Policy Paper on Sustainable Agriculture in the Danube River Basin. International Commission for the Protection of the Danube River (ICPDR), Vienna, Austria. https://www.icpdr.org/sites/default/files/nodes/documents/icpdr_policy_paper_on_sustainable_agriculture.pdf

ICPDR (2024): Expert Groups. International Commission for the Protection of the Danube River (ICPDR), Vienna, Austria. https://www.icpdr.org/about-icpdr/organisation/expert-task-groups (last access: 19 February 2024)

ICPDR/LMU (2018): Revision and update of the Danube Study. Integrating and editing new scientific results in climate change research and the resulting impacts on water availability to revise the existing adaptation strategies in the Danube River basin. https://www.icpdr.org/sites/default/files/nodes/documents/danube_climate_adaptation_study_2018.pdf

IEA (2016): World Energy Outlook 2016. International Energy Agency, Paris, France. https://www.iea.org/reports/world-energy-outlook-2016

IEA (2021): Hydropower Special Market Report. International Energy Agency, Paris, France. https://www.iea.org/reports/hydropower-special-market-report

IPBES (2019): Summary for policymakers of the global assessment report on biodiversity and ecosystem services. In: Díaz, S., Settele, J., Brondizio, E.S., Ngo, H.T., Gueze, M., Agard, J., Arneth, A., Balvanera, P., Brauman, K.A., Butchart, S.H.M., Chan, K.M.A., Garibaldi, L.A., Ichii, K., Liu, J., Subramanian, S.M., Midgley, G.F., Miloslavich, P., Molnár, Z., Obura, D., Pfaff, A., Polasky, S., Purvis, A., Razzaque, J., Reyers, B., Roy Chowdhury, R., Shin, Y.J., Visseren-Hamakers, I.J., Willis, K.J. and Zayas, C.N. (Eds.). IPBES Secretariat, Bonn, Germany, pp. XIV-LXI. https://doi.org/10.5281/zenodo.3553458

IPCC (2013): Summary for Policymakers. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P.M. (Eds.): Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 3-29. https://doi.org/10.1017/CBO9781107415324.004

IPCC (2021): Summary for Policymakers. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R. and Zhou, B. (Eds.): Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 3-32. https://doi.org/10.1017/9781009157896.001

IPCC (2023): Summary for Policymakers. In: Core Writing Team, Lee, H. and Romero, J. (Eds.): Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland, pp. 1-34. https://doi.org/10.59327/IPCC/AR6-9789291691647.001

Isotta, F.A., Vogel, R. and Frei, C. (2015): Evaluation of European regional reanalyses and downscalings for precipitation in the Alpine region. *Meteorologische Zeitschrift*, 24(1): 15-37. https://doi.org/10.1127/metz/2014/0584

Iturbide, M., Fernández, J., Gutiérrez, J.M., Bedia, J., Cimadevilla, E., Díez-Sierra, J., Manzanas, R., Casanueva, A., Baño-Medina, J., Milovac, J., Herrera, S., Cofiño, A.S., San Martín, D., García-Díez, M., Hauser, M., Huard, D. and Yelekci, Ö. (2021):

Repository supporting the implementation of FAIR principles in the IPCC-WG1 Atlas. Zenodo. https://github.com/IPCC-WG1/Atlas (last access: 14 February 2024)

Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O.B., Bouwer, L.M., Braun, A., Colette, A., Déqué, M., Georgievski, G., Georgopoulou, E., Gobiet, A., Menut, L., Nikulin, G., Haensler, A., Hempelmann, N., Jones, C., Keuler, K., Kovats, S., Kröner, N., Kotlarski, S., Kriegsmann, A., Martin, E., van Meijgaard, E., Moseley, C., Pfeifer, S., Preuschmann, S., Radermacher, C., Radtke, K., Rechid, D., Rounsevell, M., Samuelsson, P., Somot, S., Soussana, J.-F., Teichmann, C., Valentini, R., Vautard, R., Weber, B. and Yiou, P. (2014): EURO-CORDEX: new high-resolution climate change projections for European impact research. *Regional Environmental Change*, 14(2): 563-578. https://doi.org/10.1007/s10113-013-0499-2

Jungwirth, M., Haidvogl, G., Hohensinner, S., Waidbacher, H. and Zauner, G. (2014): Österreichs Donau. Landschaft – Fisch – Geschichte. Institut für Hydrobiologie u. Gewässermanagement, BOKU Wien.

Karabulut, A., Egoh, B.N., Lanzanova, D., Grizzetti, B., Bidoglio, G., Pagliero, L., Bouraoui, F., Aloe, A., Reynaud, A., Maes, J., Vandecasteele, I. and Mubareka, S. (2016): Mapping water provisioning services to support the ecosystem–water–food–energy nexus in the Danube river basin. *Ecosystem Services*, 17: 278-292. https://doi.org/10.1016/j.ecoser.2015.08.002

Katragkou, E., Sobolowski, S.P., Teichmann, C., Solmon, F., Pavlidis, V., Rechid, D., Hoffmann, P., Fernandez, J., Nikulin, G. and Jacob, D. (2024): Delivering an improved framework for the new generation of CMIP6-driven EURO-CORDEX regional climate simulations. *Bulletin of the American Meteorological Society*. https://doi.org/10.1175/BAMS-D-23-0131.1

Kotlarski, S., Keuler, K., Christensen, O.B., Colette, A., Déqué, M., Gobiet, A., Goergen, K., Jacob, D., Lüthi, D., van Meijgaard, E., Nikulin, G., Schär, C., Teichmann, C., Vautard, R., Warrach-Sagi, K. and Wulfmeyer, V. (2014): Regional climate modeling on European scales: a joint standard evaluation of the EURO-CORDEX RCM ensemble. *Geoscientific Model Development*, 7(4): 1297-1333. https://doi.org/10.5194/gmd-7-1297-2014

Kotlarski, S., Szabó, P., Herrera, S., Räty, O., Keuler, K., Soares, P.M., Cardoso, R.M., Bosshard, T., Pagé, C., Boberg, F., Gutiérrez, J.M., Isotta, F.A., Jaczewski, A., Kreienkamp, F., Liniger, M.A., Lussana, C. and Pianko-Kluczyńska, K. (2019): Observational uncertainty and regional climate model evaluation: A pan-European perspective. *International Journal of Climatology*, 39(9): 3730-3749. https://doi.org/10.1002/joc.5249

Lehner, B., Verdin, K. and Jarvis, A. (2008): New Global Hydrography Derived From Spaceborne Elevation Data. *Eos*, 89(10): 93-94. https://doi.org/10.1029/2008EO100001

MADR (2019): Strategia națională de reabilitare şi extindere a infrastructurii de irigaţii din România. LEX-FAOC202236. Ministerul Agriculturii şi Dezvoltării Rurale (MADR), Bucharest, Romania. https://www.fao.org/faolex/results/details/en/c/LEX-FAOC202236/

MAEP (2015): Executive Summary for the Water Management Strategy of the territory of the Republic of Serbia. Ministry of Agriculture and Environmental Protection (MAEP), Water Directorate, Republic of Serbia, Belgrade, Serbia. https://rdvode.gov.rs/doc/dokumenta/javne-rasprave/strategija/Strategija%20SUMMARY.pdf

Maraun, D., Wetterhall, F., Ireson, A.M., Chandler, R.E., Kendon, E.J., Widmann, M., Brienen, S., Rust, H.W., Sauter, T., Themeßl, M., Venema, V.K.C., Chun, K.P., Goodess, C.M., Jones, R.G., Onof, C., Vrac, M. and Thiele-Eich, I. (2010): Precipitation downscaling under climate change: Recent developments to bridge the gap between dynamical models and the end user. *Reviews of Geophysics*, 48(3). https://doi.org/10.1029/2009RG000314

Maraun, D. and Widmann, M. (2018a): Climate Modelling. In: Maraun, D. and Widmann, M. (Eds.): Statistical Downscaling and Bias Correction for Climate Research. Cambridge University Press, Cambridge, pp. 96-122. https://doi.org/10.1017/9781107588783.009

Maraun, D. and Widmann, M. (2018b): Model Output Statistics. In: Maraun, D. and Widmann, M. (Eds.): Statistical Downscaling and Bias Correction for Climate Research. Cambridge University Press, Cambridge, pp. 170-200. https://doi.org/10.1017/9781107588783.013

Marke, T., Mauser, W., Pfeiffer, A. and Zängl, G. (2011): A pragmatic approach for the downscaling and bias correction of regional climate simulations: evaluation in hydrological modeling. *Geoscientific Model Development*, 4(3): 759-770. https://doi.org/10.5194/gmd-4-759-2011

Marke, T., Mauser, W., Pfeiffer, A., Zängl, G., Jacob, D. and Strasser, U. (2014): Application of a hydrometeorological model chain to investigate the effect of global boundaries and downscaling on simulated river discharge. *Environmental Earth Sciences*, 71(11): 4849-4868. https://doi.org/10.1007/s12665-013-2876-z

Mauser, W. (2009): Water Resources – Efficient, Sustainable and Equitable Use. Haus Publishing, London.

Mauser, W. and Bach, H. (2009): PROMET – Large scale distributed hydrological modelling to study the impact of climate change on the water flows of mountain watersheds. *Journal of Hydrology*, 376(3): 362-377. https://doi.org/10.1016/j.jhydrol.2009.07.046

Mauser, W., Bach, H., Frank, T., Hank, T., Koch, F., Marke, T., Muerth, M., Prasch, M., Strasser, U. and Zabel, F. (2015a): PROMET – Processes of Mass and Energy Transfer. An Integrated Land Surface Processes and Human Impacts Simulator for the Quantitative Exploration of Human-Environment Relations. Part 1: Algorithms Theoretical Baseline Document, v 5.8. Ludwig-Maximilians-Universität München. https://www.geographie.uni-muenchen.de/department/fiona/forschung/projekte/promet_handbook/promethandbook1.pdf

Mauser, W., Klepper, G., Zabel, F., Delzeit, R., Hank, T., Putzenlechner, B. and Calzadilla, A. (2015b): Global biomass production potentials exceed expected future demand without the need for cropland expansion. *Nature Communications*, 6: 8946. https://doi.org/10.1038/ncomms9946

Mekonnen, M.M. and Hoekstra, A.Y. (2011): The green, blue and grey water footprint of crops and derived crop products. *Hydrology and Earth System Sciences*, 15(5): 1577-1600. https://doi.org/10.5194/hess-15-1577-2011

Mekonnen, M.M. and Hoekstra, A.Y. (2016): Four billion people facing severe water scarcity. *Science Advances*, 2(2): e1500323. https://doi.org/10.1126/sciadv.1500323

Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., van Vuuren, D.P., Carter, T.R., Emori, S., Kainuma, M., Kram, T., Meehl, G.A., Mitchell, J.F.B., Nakicenovic, N., Riahi, K., Smith, S.J., Stouffer, R.J., Thomson, A.M., Weyant, J.P. and Wilbanks, T.J. (2010): The next generation of scenarios for climate change research and assessment. *Nature*, 463: 747-756. https://doi.org/10.1038/nature08823

Muerth, M.J., Gauvin St-Denis, B., Ricard, S., Velázquez, J.A., Schmid, J., Minville, M., Caya, D., Chaumont, D., Ludwig, R. and Turcotte, R. (2013): On the need for bias correction in regional climate scenarios to assess climate change impacts on river runoff. *Hydrology and Earth System Sciences*, 17(3): 1189-1204. https://doi.org/10.5194/hess-17-1189-2013

Muñoz-Sabater, J., Dutra, E., Agustí-Panareda, A., Albergel, C., Arduini, G., Balsamo, G., Boussetta, S., Choulga, M., Harrigan, S., Hersbach, H., Martens, B., Miralles, D.G., Piles, M., Rodríguez-Fernández, N.J., Zsoter, E., Buontempo, C. and Thépaut, J.N. (2021): ERA5-Land: a state-of-the-art global reanalysis dataset for land applications. *Earth System Science Data*, 13(9): 4349-4383. https://doi.org/10.5194/essd-13-4349-2021

NE (2024): 1:10m Cultural Vectors. Natural Earth (NE). https://www.naturalearthdata.com/downloads/10m-cultural-vectors/ (last access: 12 February 2024)

Neubarth, J. (2020): Social and economic drivers for hydropower development in Danube countries. e3 consult GmbH, Innsbruck, Austria. https://www.doi.org/10.13140/RG.2.2.29787.72482

O'Neill, B.C., Kriegler, E., Riahi, K., Ebi, K.L., Hallegatte, S., Carter, T.R., Mathur, R. and van Vuuren, D.P. (2014): A new scenario framework for climate change research: the concept of shared socioeconomic pathways. *Climatic Change*, 122(3): 387-400. https://doi.org/10.1007/s10584-013-0905-2

OECD (2021): Agriculture and water policies: main characteristics and evolution from 2009 to 2019. Hungary. Organisation for Economic Co-operation and Development (OECD), Paris, France. https://www.oecd.org/agriculture/topics/water-and-agriculture/documents/oecd-water-policies-country-note-hungary.pdf

Pagano, T. and Sorooshian, S. (2002): Hydrologic Cycle. In: MacCracken, M.C. and Perry, J.S. (Eds.): The Earth system: physical and chemical dimensions of global environmental change. Encyclopedia of Global Environmental Change. John Wiley & Sons, Chichester, pp. 450-464.

Pistocchi, A., Beck, H., Bisselink, B., Gelati, E., Lavalle, C. and Feher, J. (2015): Water scenarios for the Danube River Basin. Elements for the assessment of the Danube agriculture-energy-water nexus. EUR 27700 EN, JRC99843, Publications Office of the European Union, Luxembourg. https://doi.org/10.2788/375680

Prein, A.F. and Gobiet, A. (2017): Impacts of uncertainties in European gridded precipitation observations on regional climate analysis. *International Journal of Climatology*, 37(1): 305-327. https://doi.org/10.1002/joc.4706

Probst, E., Fader, M. and Mauser, W. (2024): The water-energy-food-ecosystem nexus in the Danube River Basin: Exploring scenarios and implications of maize irrigation. *Science of The Total Environment*, 914: 169405. https://doi.org/10.1016/j.scitotenv.2023.169405

Probst, E. and Mauser, W. (2022): Evaluation of ERA5 and WFDE5 forcing data for hydrological modelling and the impact of bias correction with regional climatologies: A case study in the Danube River Basin. *Journal of Hydrology: Regional Studies*, 40: 101023. https://doi.org/10.1016/j.ejrh.2022.101023

Probst, E. and Mauser, W. (2023): Climate Change Impacts on Water Resources in the Danube River Basin: A Hydrological Modelling Study Using EURO-CORDEX Climate Scenarios. *Water*, 15(1): 8. https://doi.org/10.3390/w15010008

Reis, A.A.d., Weerts, A., Ramos, M.-H., Wetterhall, F. and Fernandes, W.d.S. (2022): Hydrological data and modeling to combine and validate precipitation datasets relevant to hydrological applications. *Journal of Hydrology: Regional Studies*, 44: 101200. https://doi.org/10.1016/j.ejrh.2022.101200

Rockel, B. (2015): The Regional Downscaling Approach: a Brief History and Recent Advances. *Current Climate Change Reports*, 1(1): 22-29. https://doi.org/10.1007/s40641-014-0001-3

Schiller, H., Miklós, D. and Sass, J. (2010): Chapter 2. The Danube River and its Basin Physical Characteristics, Water Regime and Water Balance. In: Brilly, M. (Ed.): Hydrological Processes of the Danube River Basin. Springer, Dordrecht, Heidelberg, London, New York, pp. 25-77.

Schwalm, C.R., Glendon, S. and Duffy, P.B. (2020): RCP8.5 tracks cumulative CO_2 emissions. *Proceedings of the National Academy of Sciences*, 117(33): 19656-19657. https://doi.org/10.1073/pnas.2007117117

Seneviratne, S.I., Zhang, X., Adnan, M., Badi, W., Dereczynski, C., Di Luca, A., Ghosh, S., Iskandar, I., Kossin, J., Lewis, S., Otto, F., Pinto, I., Satoh, M., Vicente-Serrano, S.M., Wehner, M. and Zhou, B. (2021): Weather and Climate Extreme Events in a Changing Climate. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R. and Zhou, B. (Eds.): Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1513-1766. https://doi.org/10.1017/9781009157896.013

Sevruk, B. (2006): Rainfall measurement: gauges. In: Anderson, M.G. (Ed.): Encyclopedia of Hydrological Sciences. Part 4 Hydrometeorology. Wiley & Sons Ltd, Chichester, UK, pp. 7.

Shiklomanov, I.A. (1993): World Freshwater Resources. In: Gleick, P.H. (Ed.): Water in Crisis: A Guide to World's Freshwater Resources. Oxford University Press, New York, pp. 13-24.

Shiklomanov, I.A. (Ed.) (1997): Assessment of water resources and water availability in the world. World Meteorological Organization, Geneva.

Shiklomanov, I.A. (2009): The Hydrological Cycle. In: Shiklomanov, I.A. (Ed.): The Hydrological Cycle. Encyclopedia of Life Support Systems (EOLSS). EOLSS Publishers / UNESCO, Oxford, pp. 1-67.

Siad, S.M., Iacobellis, V., Zdruli, P., Gioia, A., Stavi, I. and Hoogenboom, G. (2019): A review of coupled hydrologic and crop growth models. *Agricultural Water Management*, 224: 105746. https://doi.org/10.1016/j.agwat.2019.105746

Siebert, S., Henrich, V., Frenken, K. and Burke, J. (2013): Update of the digital global map of irrigation areas to version 5. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy. https://doi.org/10.13140/2.1.2660.6728

Skinner, C.B., Poulsen, C.J., Chadwick, R., Diffenbaugh, N.S. and Fiorella, R.P. (2017): The Role of Plant CO2 Physiological Forcing in Shaping Future Daily-Scale Precipitation. *Journal of Climate*, 30(7): 2319-2340. https://doi.org/10.1175/JCLI-D-16-0603.1

Sommerwerk, N., Hein, T., Schneider-Jacoby, M., Baumgartner, C., Ostojić, A., Siber, R., Bloesch, J., Paunović, M. and Tockner, K. (2009): Chapter 3 - The Danube River Basin. In: Tockner, K., Uehlinger, U. and Robinson, C.T. (Eds.): Rivers of Europe. Academic Press, London, pp. 59-112. https://doi.org/10.1016/B978-0-12-369449-2.00003-5

Stagl, J.C. and Hattermann, F.F. (2015): Impacts of Climate Change on the Hydrological Regime of the Danube River and Its Tributaries Using an Ensemble of Climate Scenarios. *Water*, 7(11): 6139-6172. https://doi.org/10.3390/w7116139

Stagl, J.C. and Hattermann, F.F. (2016): Impacts of Climate Change on Riverine Ecosystems: Alterations of Ecologically Relevant Flow Dynamics in the Danube River and Its Major Tributaries. *Water*, 8(12): 566. https://doi.org/10.3390/w8120566

Stolz, R., Prasch, M., Weber, M., Koch, F., Weidinger, R., Ebner, M. and Mauser, W. (2018): Climate Change Impacts on the Water Resources in the Danube River Basin and Possibilities to Adapt – The Way to an Adaptation Strategy and its Update. *Journal of Environmental Geography*, 11(3-4): 13-24. https://doi.org/10.2478/jengeo-2018-0009

Taylor, K.E., Stouffer, R.J. and Meehl, G.A. (2012): An Overview of CMIP5 and the Experiment Design. *Bulletin of the American Meteorological Society*, 93(4): 485-498. https://doi.org/10.1175/bams-d-11-00094.1

Teutschbein, C. and Seibert, J. (2010): Regional Climate Models for Hydrological Impact Studies at the Catchment Scale: A Review of Recent Modeling Strategies. *Geography Compass*, 4(7): 834-860. https://doi.org/10.1111/j.1749-8198.2010.00357.x

Teutschbein, C. and Seibert, J. (2012): Bias correction of regional climate model simulations for hydrological climate-change impact studies: Review and evaluation of different methods. *Journal of Hydrology*, 456-457: 12-29. https://doi.org/10.1016/j.jhydrol.2012.05.052

Todini, E. (2007): A mass conservative and water storage consistent variable parameter Muskingum-Cunge approach. *Hydrology and Earth System Sciences*, 11(5): 1645-1659. https://doi.org/10.5194/hess-11-1645-2007

UN-Water (2013): Water Security & the Global Water Agenda. A UN-Water Analytical Brief. United Nations University, Hamilton, Canada. https://www.unwater.org/publications/water-security-and-global-water-agenda

UN (2022): World Population Prospects 2022: Summary of Results. UN DESA/POP/2022/TR/NO. 3. United Nations (UN), Department of Economic and Social

Affairs, Population Division, New York, USA. https://desapublications.un.org/file/989/download

UN (2023): The United Nations World Water Development Report 2023: Partnerships and Cooperation for Water. UN (United Nations), UNESCO, Paris. https://www.unwater.org/publications/un-world-water-development-report-2023

UN General Assembly (2015): Transforming Our World: The 2030 Agenda for Sustainable Development, 21 October 2015, A/RES/70/1. United Nations. https://www.refworld.org/docid/57b6e3e44.html

UNECE (2016): Reconciling resource uses in transboundary basins: assessment of the water-food-energy-ecosystems nexus in the Sava River Basin. United Nations Economic Commission for Europe, New York, Geneva. https://unece.org/environment-policy/publications/reconciling-resource-uses-transboundary-basins-assessment-water-3

UNECE (2018): Methodology for assessing the water-food-energy-ecosystems nexus in transboundary basins and experiences from its application: synthesis. United Nations Economic Commission for Europe (UNECE), New York, Geneva. https://unece.org/environment-policy/publications/methodology-assessing-water-food-energy-ecosystems-nexus

UNESCO/UN-Water (2020): United Nations World Water Development Report 2020: Water and Climate Change. UNESCO, Paris. https://www.unwater.org/publications/un-world-water-development-report-2020

UNFCCC (2016): The Paris Agreement. United Nations Framework Convention on Climate Change (UNFCCC). https://unfccc.int/documents/184656

van Dijk, M., Morley, T., Rau, M.L. and Saghai, Y. (2021): A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050. *Nature Food*, 2(7): 494-501. https://doi.org/10.1038/s43016-021-00322-9

van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S.J. and Rose, S.K. (2011): The representative concentration pathways: an overview. *Climatic Change*, 109(1): 5. https://doi.org/10.1007/s10584-011-0148-z

van Vuuren, D.P., Kriegler, E., O'Neill, B.C., Ebi, K.L., Riahi, K., Carter, T.R., Edmonds, J., Hallegatte, S., Kram, T., Mathur, R. and Winkler, H. (2014): A new scenario framework for Climate Change Research: scenario matrix architecture. *Climatic Change*, 122(3): 373-386. https://doi.org/10.1007/s10584-013-0906-1

Wada, Y. and Bierkens, M.F.P. (2014): Sustainability of global water use: past reconstruction and future projections. *Environmental Research Letters*, 9(10): 104003. https://doi.org/10.1088/1748-9326/9/10/104003

WCRP-CORDEX (2023): CORDEX simulations status. https://wcrp-cordex.github.io/simulation-status// (last access: 22 February 2024)

Weitz, N., Strambo, C., Kemp-Benedict, E. and Nilsson, M. (2017): Governance in the water-energy-food nexus: Gaps and future research needs. SEI Working Paper 2017-07, Stockholm Environment Institute, Stockholm. https://www.sei.org/publications/water-energy-food-governance/

World Bank Group (2018): Romania Water Diagnostic Report: Moving toward EU Compliance, Inclusion, and Water Security. World Bank, Washington, DC. http://hdl.handle.net/10986/29928

WWAP (2015): The United Nations World Water Development Report 2015: Water for a Sustainable World. WWAP (United Nations World Water Assessment Programme), UNESCO, Paris. https://www.unwater.org/publications/un-world-water-development-report-2015

WWAP/UN-Water (2018): The United Nations World Water Development Report 2018: Nature-Based Solutions for Water. WWAP (United Nations World Water Assessment Programme), UN-Water, UNESCO, Paris. https://www.unwater.org/publications/world-water-development-report-2018

Yin, X. and van Laar, H.H. (2005): Crop Systems Dynamics: An ecophysiological simulation model for genotype-by-environment interactions. Wageningen Academic Publishers, Wageningen, NL.

Zhang, Y., Wu, Z., Singh, V.P., He, H., He, J., Yin, H. and Zhang, Y. (2021): Coupled hydrology-crop growth model incorporating an improved evapotranspiration module. *Agricultural Water Management*, 246: 106691. https://doi.org/10.1016/j.agwat.2020.106691

Zwart, S.J. and Bastiaanssen, W.G.M. (2004): Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. *Agricultural Water Management*, 69(2): 115-133. https://doi.org/10.1016/j.agwat.2004.04.007

Appendix A: Paper I

Paper I: Evaluation of ERA5 and WFDE5 Forcing Data for Hydrological Modelling and the Impact of Bias Correction with Regional Climatologies: A Case Study in the Danube River Basin

Reference: Probst, E. and Mauser, W. (2022): Evaluation of ERA5 and WFDE5 forcing data for hydrological modelling and the impact of bias correction with regional climatologies: A case study in the Danube River Basin. *Journal of Hydrology: Regional Studies*, 40: 101023. https://doi.org/10.1016/j.ejrh.2022.101023

Author Contributions: Conceptualization, E.P. and W.M.; Methodology, E.P. and W.M.; Software, E.P. and W.M.; Validation, E.P.; Formal analysis, E.P.; Investigation, E.P.; Resources, W.M.; Data curation, E.P.; Writing—original draft preparation, E.P.; Writing—review & editing, E.P. and W.M.; Visualization, E.P.; Supervision, W.M.; Project administration, W.M.; Funding acquisition, W.M.

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Appendix B.1: Paper II

Paper II: The Water-Energy-Food-Ecosystem Nexus in the Danube River Basin: Exploring Scenarios and Implications of Maize Irrigation

Reference: Probst, E., Fader, M. and Mauser, W. (2024): The water-energy-food-ecosystem nexus in the Danube River Basin: Exploring scenarios and implications of maize irrigation. *Science of The Total Environment*, 914: 169405. https://doi.org/10.1016/j.scitotenv.2023.169405

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Appendix B.2: Paper II – Supplementary Data

Supplementary Material to:

Paper II: The Water-Energy-Food-Ecosystem Nexus in the Danube River Basin: Exploring Scenarios and Implications of Maize Irrigation

Reference: Probst, E., Fader, M. and Mauser, W. (2024): The water-energy-food-ecosystem nexus in the Danube River Basin: Exploring scenarios and implications of maize irrigation. Supplementary data. *Science of The Total Environment*, 914: 169405. https://doi.org/10.1016/j.scitotenv.2023.169405

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Appendix C: Paper III

Paper III: Climate Change Impacts on Water Resources in the Danube River Basin: A Hydrological Modelling Study Using EURO-CORDEX Climate Scenarios

Reference: Probst, E. and Mauser, W. (2023): Climate Change Impacts on Water Resources in the Danube River Basin: A Hydrological Modelling Study Using EURO-CORDEX Climate Scenarios. *Water*, 15(1): 8. https://doi.org/10.3390/w15010008

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