

Climate Change Adaptation: Scenario Modelling and Insights into the Energy-Water-Land Nexus

by

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B.Sc., National University of Computer & Emerging Sciences, 2016

M.Sc., Technical University Dresden, 2019

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Abstract

Climate change involves complex interactions with various sectors, such as energy, water, land, and socio-economic systems. To achieve the global warming target of "well below 2°C," the international community must address Sustainable Development Goals (SDGs) such as clean energy, water and sanitation systems, and food security. A multi-sector perspective is crucial for developing sustainable policies. Integrated Assessment Models (IAMs) are essential for analyzing long-term consequences of diverse socio-economic trajectories and climate change scenarios. However, IAMs may not fully capture the intricacies of adaptations at the local or national level. Understanding adaptation and its interaction with mitigation strategies is crucial for developing successful climate strategies. Quantitative assessments of adaptation are crucial for understanding vulnerability and providing an incomplete picture of the overall climate challenge.

Using the MESSAGEix Integrated Assessment Framework, this thesis explores the capability of the IAM to address adaptation using the Indus River Basin as an example and the adaptation of the river under socio-economic, energy, water, and land resource constraints. It allows us to understand the challenges associated with formulating scenarios addressing climate impacts and adaptation. The thesis then builds upon this foundation by introducing a novel framework developed at a global level, the MESSAGEix Nexus. This framework integrates the water sector with existing energy and land systems at high spatial resolution. In addition, it includes biophysical climate impacts throughout the Energy-Water-Land (EWL) nexus using the outputs from Climate Impact Models. This framework is designed to be scalable and open-source and has already been applied at the country scale for Zambian EWL nexus analysis. In a multi-model comparative analysis, the common scenarios from the MESSAGEix-Nexus model and the IMAGE IAM are compared to look more closely at how adaptation and mitigation work together and against each other. This analysis also presents the concept of a "Climate Resilient development scenario," which, while recognizing the effects of climate change, emphasizes adaptive capacities in the context of sustainable development objectives and highlights the central role of the water system in climate change assessments.

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Chapter 1 Introduction

Climate change demonstrates complex interactions with multiple sectors, including energy, water, land, and socioeconomic systems. The existence of these interdependencies underscores the need for an integrated approach to formulating sustainable policies that effectively tackle the complex challenges of the 21st century (Khan et al., 2017). In the pursuit of attaining the global warming target of "well below 2°C," the international community is confronted with the challenge of addressing many Sustainable Development Goals (SDGs). These goals encompass a range of critical issues, including the provision of clean energy, the preservation of water and sanitation systems, and the assurance of food security (Soergel, Kriegler, Bodirsky, et al., 2021; D. P. van Vuuren et al., 2022). This multifaceted agenda demands simultaneous consideration and action. The inclusion of inter-sectoral goals is crucial in the development of policies that are both successful and sustainable over the long term (Soergel, Kriegler, Weindl, et al., 2021). A multi-sector perspectives and study of these challenges is increasingly recognized as a relevant perspective, especially considering Climate change & Sustainable Development Goals, in order to foster mutually beneficial interactions and mitigate unexpected consequences. The core of this interconnected network is comprised of the energy, water, and land sectors (EWL), which have garnered significant attention due to their interdependent characteristics (Rasul, 2016; Schleussner et al., 2021) (Khan et al., 2022; Mpandeli et al., 2018a; Rasul & Sharma, 2016b; Vinca et al., 2021). Tackling the complexities of this extensive network poses threats to vulnerable communities, particularly when combined with constrained resources, escalating demands due to population increase (Byers et al., 2018).

Integrated Assessment Models (IAMs) are widely recognized as crucial instruments for researchers and policymakers alike. They facilitate the analysis of the long-term consequences of diverse socioeconomic trajectories and different climate change scenarios (Riahi et al., 2017a). The Shared Socioeconomic Pathways (SSPs) and Representation Concentration Pathways (RCPs) are narrative frameworks that offer

structured scenarios for forecasting the trajectories of global development, particularly in the context of climate change (O'Neill et al., 2017; D. P. van Vuuren et al., 2011) IAMS has been widely utilized for accessing EWL pathways and their interconnectedness across scales; global (Dolan et al., 2021; Hejazi et al., 2014; Kim et al., 2016; Pastor et al., 2019a), country (Binsted et al., 2021; Cullenward et al., 2020) (Köberle et al., 2021; van Maanen et al., 2023), basin (Vinca, Parkinson, Riahi, et al., 2020). However, the utilization of IAM scenarios has played a crucial role in bringing attention to the difficulties associated with mitigation efforts and the necessity of climate adaptation across EWL sectors. The lack of full integration of climate impacts across different sectors, as noted by . The frequently employed macroscopic viewpoint of Integrated Assessment Models (IAMs) may not always adequately capture the intricacies associated with adaptations at the local or national level (Andrijevic et al., 2023). Therefore, it is essential to include climate impacts within the IAMs scenarios to be able to see revised costs of mitigation, tradeo-offs, and synergies across multi sectoral objectives for effective climate policies (Köberle et al., 2021; Payet-Burin, 2022; Piontek et al., 2021a; van Maanen et al., 2023; Yalew et al., 2020a).

In conclusion, as this thesis progresses further into later chapters, it becomes evident that addressing the complexities of climate change necessitates the integration of diverse techniques, comprehensive approaches, and a nuanced comprehension of the interconnectedness among different sectors.

1.1 The Use of Integrated Assessment Models in Climate Change Research

It is crucial to reflect on the philosophical underpinnings of the selected approaches and use of IAM in this dissertation. IAM is used as a guiding tool in this dissertation to negotiate the intricate challenges of climate change. The idea of IAMs embodies a profound sense of interconnectivity, effectively coordinating diverse sectors such as energy, water, and land in a harmonic manner for analysis. This comprehensive method reveals a wide-ranging perspective of sustainable routes, enhanced by the various yet interrelated aspects of global sustainability challenges.

When considering multiple approaches, one could question if there could have been an alternative path. Multiple models and methodologies, such as process-based or econometric models, are available as potential options. Nevertheless, these routes, although valuable, may not cover the multi-sectoral integration landscape as

comprehensively as IAMs . The selection of IAMs represents a philosophical orientation, a dedication to a course of action that recognizes and prioritizes the complex network of interconnections within our worldwide environment (References).

Ultimately, the selection of IAMs is not solely a matter of methodology, but rather a reflection of one's philosophical position. The statement demonstrates a commitment to fully understanding the complex aspects of climate change. It emphasizes the importance of conducting research that not only explores theoretical concepts but also effectively contributes to the development of policies and sustainable initiatives.

1.2 Research Question & Outline

Understanding adaptation gaps and capacity is critical in determining how detrimental climate change impacts will be for different population groups, sectors, and regions. The IPCC's latest assessment report finds that limits to adaptation will be reached with increasing warming, further demonstrating that implicit adaptation will not be enough to counter the mounting impacts of climate change. Understanding what adaptation can accomplish and how it interacts with mitigation strategies is critical to developing successful climate strategies. Quantitative assessments of adaptation, integrated into projections of impacts and mitigation, will be decisive in building this understanding. In general, it is essential to be transparent about how comprehensive the models are to be sure whether questions can be answered. The current absence of adaptation in most quantitative assessments of climate change and the lack of a comprehensive representation of impacts in IAMs limits understanding of the vulnerability of regions, countries and societies and provides an incomplete picture of the overall scale of the climate challenge.

With the above context and the gaps in IAM scenarios, the thesis attempts to answer the following key research question:

How do adaptation and mitigation strategies for climate change interrelate, and what are the inherent trade-offs and synergies ?

In order to address the fundamental question, the MESSAGEix Integrated Assessment Framework developed by (Huppmann et al., 2019) has been utilized. In order to understand the limitations of existing Chapter 2 discusses the use of the multi-sector Integrated Assessment Model (IAM) developed for the Indus River Basin,

known as the Nexus Solutions Tool (NEST) (Vinca, Parkinson, Byers, et al., 2020a). The research analyzes the implementation of environmental flow limits in the Indus River delta, which is characterized by high levels of stress. This study reveals the limitations and parameters of various adaptation solutions. This investigation highlights the dichotomy between the elevated levels of stress in the basin and the necessity for the sustainability of the river system. This study motivates us to expand on similar analyses on a global scale.

Chapter 3 discusses the MESSAGEix-Nexus framework developed as part of this thesis. The key novelty is that it includes the water sector at a high spatial resolution with the existing energy and land systems and biophysical climate impacts across EWL systems. The framework is designed to be adaptable at multiple scales and expanded in the future by making the development open-source in line with cutting-edge software practices. The framework is already being utilized for the Zambian EWL nexus analysis (Falchetta et al., 2022a).

In Chapter 4, a more comprehensive exploration of the fundamental research question is undertaken, utilizing the MESSAGEix Nexus framework to present an analysis of the scenarios. Through the juxtaposition of these scenarios with equivalent assumptions from the IMAGE Integrated Assessment Model (IAM), the research takes on the form of a multi-model comparative study. This chapter presents the novel "Climate Resilient Development" scenario concept. This scenario acknowledges the consequences of climate change and highlights the ability to adapt while emphasizing the water system's significant role in climate change evaluations.

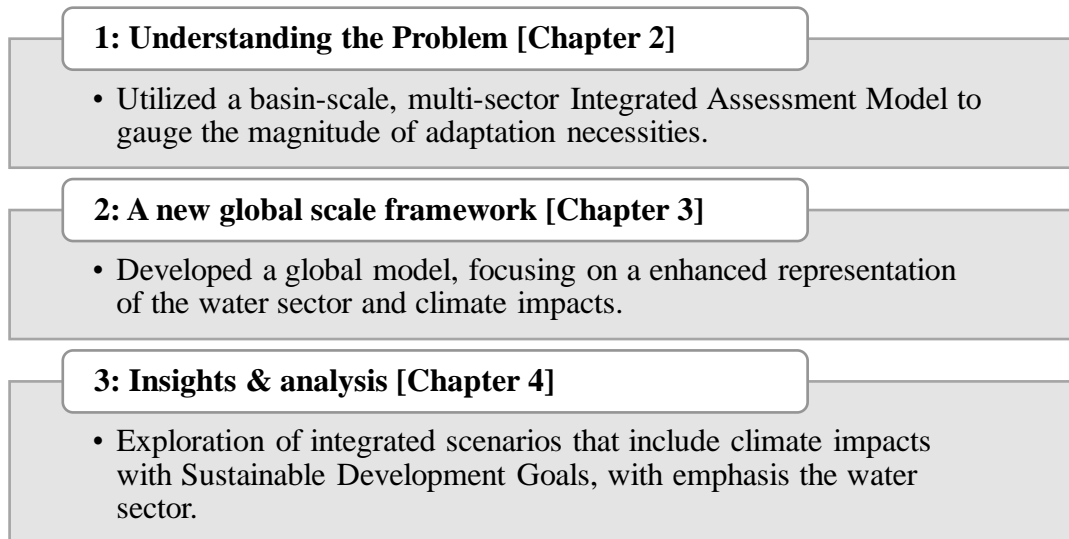


Figure 1.1 Schematic diagram of mapping research objectives to each chapter

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Chapter 2 Replenishing Indus Delta through Multisector transformation¹

Preamble. The Indus River Basin (IRB) is a severely water-stressed and rapidly developing South Asia home to an estimated 250 million people. An acute deficit of environmental flows (EF) in the basin's delta negatively impacts geomorphology and surrounding ecosystems. Here, a sub-national model of the IRB's integrated water-energy-land systems is applied to quantify multi-sector transformations and system costs for enhancing EFs to the Indus Delta. The results show that increasing average outflows from the basin relative to historical policy levels by 2.5 and 5 times would increase sectoral costs for upstream water users between 17- 32 and 68-72 % for low and high ecological potential targets. The enhanced EFs result in more energy for pumping and treating water upstream from the delta and a net increase in irrigation and energy investments. The EF policy costs are minimized by 7-14% through cooperation across countries and 6-9% through the coordinated implementation of water efficiency measures in the irrigation, conveyance, power plant cooling, and water treatment sectors. The results underscore the crucial role of multi-sector, multi-scale collaboration in achieving EF targets in water-stressed river basins for ecosystem-adaptation to climate vulnerability, restoration of delta and socio-economic benefits in lower IRB.

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2.1 Introduction

Environmental flows (EFs) are defined as the quality, quantity, and patterns of river flow required for maintaining ecosystem services, and are associated with a river's natural flow regime before human settlement (LeRoy Poff et al., 1997; Richter et al., 2006). EFs support sedimentation transfer to coastal deltas formed at the river mouth. Globally, deltas are important economic regions, occupying only 1% of the total land area but supporting 7% of the world population (Ericson et al., 2006). Reduced EFs impact the geomorphology of delta regions, re-shaping river connections, creating seismic hazards, and lowering land and groundwater quality (LeRoy Poff et al., 1997; Arthington, 2012). Reduced EFs concentrate pollutants released into rivers and reduce oxygenation levels for aquatic species (Arthington, 2012). Maintaining EFs under future population growth is thus an important strategy for the sustainable development of delta regions (Tharme, 2003).

The environmental flow assessment methodologies that are currently in use depend on linkages to other local policy recommendations and stakeholder engagement (Hill Clarvis, Allan, and Hannah, 2014; Hannaford, 2015). There are ongoing efforts in defining standards and methods to account for environmental flow methods in rivers based on the ecohydrological relationships in rivers (Richter et al., 2006). More than 200 environmental flow assessment methods exist globally (Tharme, 2003). There are numerous studies for environmental flow assessment methods and practicality of methods for river users from hydrological (Tenant, Tessamann, etc.), hydraulic, habitat-simulation, holistic methods applied in several case studies and global scale hydrological models (Pastor et al., 2014). Supplementary section S1 discusses EF methods in detail.

Defining presumptive standards and constraining the environmental flows in highly modified rivers can be a challenging task since it becomes infeasible to see the river in terms of the natural flow regime when the natural flow regime is so disturbed (Acreman et al., 2014). (Yarnell et al., 2015) characterizes highly modified rivers as; i) a high proportion converted to reservoirs, ii) most of their annual streamflow is diverted for human uses, iii) have a high proportion of their length channelized/lined. Although not all characteristics can occur in the same river at one time, the presence of any one of the characteristics in a river can make it a highly modified river (Yarnell et al., 2015). Maintaining a trade-off as per human demands and fulfilling the environmental flow requirements can be a quite complicated and challenging task for river managers,

therefore a designer approach to defining environmental flow was proposed for highly modified rivers. A designer approach suits such rivers, where achieving ecological potential and saving biodiversity is a target, considering the societal demands for highly modified rivers instead of taking the natural flow regime as a reference (Acreman et al., 2014). Constraining water withdrawals can enhance environmental flows in deltas (Richter, 2009; Gleeson and Richter, 2018), but limits growth in upstream activities reliant on water. This trade-off is challenging for regions where water is scarce but also in high demand because of the relative cost of alternative freshwater supply options. (Wu et al., 2021) carried out a detailed study for the environmental flow planning for highly modified rivers in China which also supports the narrative of the designer approach for constraining flows in such rivers.

With increasing climate vulnerability and limited water, energy and land resources, the developing regions face complex challenges for the provision of enough resources to the growing population. The issues and challenges in these sectors are complex and have a high degree of interdependency (Rasul, 2014). Therefore, a multi-sector approach to solve the challenge is required for policy analysis and climate adaptation to the vulnerability of exposed resources. South Asia has been recognized as one of the most vulnerable regions in the world due to pressure on limited resources (Rasul, 2014; Byers et al., 2018). Thus, an integrated model for energy, water, and land systems is beneficial to inform stakeholders and policymakers about the utility of different sectors and national and international planning for a sustainable and healthy future (Khan, Linares, and García-González, 2017). However, with regards to the threats, of climate change, rising population demands and stresses resources, an integrated assessment that considers water, energy and land systems as interdependent systems is crucial for sustainable decision making. These interdependent systems are crucial for a sustainable future to meet demands and ecosystems services (Khan, Linares, and García-González, 2017; Parkinson et al., 2018; Cazcarro et al., 2021).

There have been several integrated analyses for addressing the challenges of water, energy, and food for the Indus River Basin (IRB). (Yang et al., 2016) developed a hydro-agro-economic model, considering the impacts of climate changes scenarios for water allocation mechanism and infrastructure developments. (Yang et al., 2013) developed a hydro-economic model for analyzing relationships between climate, water, and agriculture sectors for IRB for prioritization and planning of future investments in the basin. Also, some studies addressed the energy use dimension of conjunctive water

management and quantified future water gaps for water supply under projected socioeconomic and climate change or gaps for estimation of energy demand variation due to groundwater pumping for agriculture (Siddiqi and Wescoat, 2013). However, there is no explicit representation of all Energy, Water and Land technologies in terms of capacities, activities, and efficiencies across spatial regions to tackle challenging and complex systems research questions (Vinca, Parkinson, Byers, et al., 2020).

In this study, we focus on the Indus River Basin (IRB) of South Asia. The IRB is one of the most water-stressed basins in the world due to irrigated food production and high population (Byers et al., 2018). Freshwater in the IRB is derived from meltwater in the Hindu-Kush-Himalaya Mountain region that flows from China, India, and Afghanistan downstream into Pakistan and draining into the Indus Delta and the Arabian Sea. Since 1869, upstream activities have caused a sediment flux reduction of 13 Mt/yr. and the delta has lost 15 out of the 16 main river channels connecting it to the sea (Syvitski et al., 2009, 2013). Policies targeting enhanced EFs are urgently needed to improve the long-term outlook for the Indus Delta region (Ali et al., 2017).

Despite the critical role of EFs in Indus Delta sustainability, there is a lack of quantitative analysis linking enhanced EF allocation policies to the adaptation costs borne by upstream sectors (Day et al., 2021). (Memon and Thapa, 2016) analyze policy and institutional analyses of the Indus delta to address the importance of complexity inherent in protecting the Indus delta. EFs in the Indus Delta is discussed in the context of Kotri barrage (a barrage located downstream of IRB for flow management) for the determination of saltwater intrusions and to accommodate fisheries (Anwar and Bhatti, 2017). Due to high demands and poor management of IRB, all the river flows are fully utilized except during the September-June season (also known as the Kharif period). The use of water upstream is limited for agriculture purposes unless additional storage reservoirs are provided. The planned hydropower projects by 2030 could enable better management of flows downstream Kotri barrage to the Arabian Sea (Tilmant, Beevers and Muyunda, 2010). If enough freshwater is available downstream of Kotri barrage, it helps to recharge aquifers and provides irrigation for agriculture in the riverine sea, maintains the salinity level in the coastal area, and provides livelihoods to the people living in the delta (González-villareal and Schultz, 2005; Anwar, Chandio and Bhalli, 2014).

The CWRAS (Country Water Resources Assistance Strategy) Pakistan, identified the ecological threats to the Indus Delta and commented that improving the environmental

flows for the restoration of ecosystems of the Indus estuary is primarily important for flow-related issues (Hirji and Davis, 2009). However, there is no explicit EF policy mentioned for the IRB as a whole nor is there an institutional mechanism in place to regulate EF allocations, even in the Indus Water Treaty that governs flow between India and Pakistan (IRSA, 1991; Anwar, Chandio and Bhalli, 2014; Anwar and Bhatti, 2017). The Water Apportionment Accord (WAA), signed in 1991 provides a legislative structure for the distribution of water to the Indus Rivers and among the province and command areas in Pakistan. The Accord describes the minimum flow requirements below Kotri barrage as 33.79 MCM/day (MCM= thousand cubic meters) (IRSA, 1991), which were reviewed by a panel of experts and changed to be 12.23 MCM/day during the June-October season (also known as Rabi Season) and 46.21 MCM/day during November-May (also known as Kharif season) in 2005 (González-villareal and Schultz, 2005). Yet there has not been integrated analysis examining how these or more ambitious targets influence upstream infrastructure decision making or investments required for EF allocation downstream.

In this paper, we incorporate enhanced delta EF policies into a multi-sector model of the IRB to address the following research questions: (1) what are potential system costs that support the allocation of delta EFs across multiple sectors and uncertainties; and (2) what are the least-cost technological changes in water, energy and land sectors that enable enhanced EF allocation for ecosystem adaptation to climate vulnerability? The study uses an engineering economic multi-sector model to answer research questions and inform policy decisions. The analysis in this paper identifies investment regimes categorized by the combined EF ambition-level and co-evolution of basin-wide water demands. It also underscores the importance of a multi-sector, multi-decadal, basin-wide approach when assessing the costs of enhanced EF allocation in water-stressed delta regions.

2.2 Methodology

2.2.1. Modelling framework & setup

This study uses an integrated economic optimization model, NEST (Vinca, Parkinson, Byers, et al., 2020), to co-optimize sub-national Energy, Water, and Land (EWL) system representation over a multi-decadal time horizon. The NExus Solutions Tool (NEST) integrates the EWL framework into the capacity expansion modelling process by jointly optimizing decisions in the water, energy, and land management sectors

(Vinca, Parkinson, Byers, et al., 2020). The objective function is the total discounted cost across all managed processes, decisions, regions, and time steps. Future costs are discounted in the objective function using an average discount rate for national planning. Input parameters include I) technology/process costs and efficiencies; ii) the historical capacities (e.g., the maximum production rate); iii) resource availability, and iv) demands. The optimization decision variables are the capacity, operation, storage, and emissions rates of technologies and processes, and the types of land-uses from the year 2020 to 2050. The decisions include the adaptive responses needed to accommodate cross-sector interactions. For example, a NEST capacity expansion scenario includes power plant capacity and fuel required to generate electricity used to pump and treat water in line with projected water demands. Likewise, NEST considers the land required for crops and the yield trade-offs associated with reduced irrigation. NEST has been developed in previous work to examine sustainable development pathways for the Indus River Basin (Vinca, Parkinson, Riahi, et al., 2020), and is adapted in this study to enable EF allocation policies at the catchment scale.

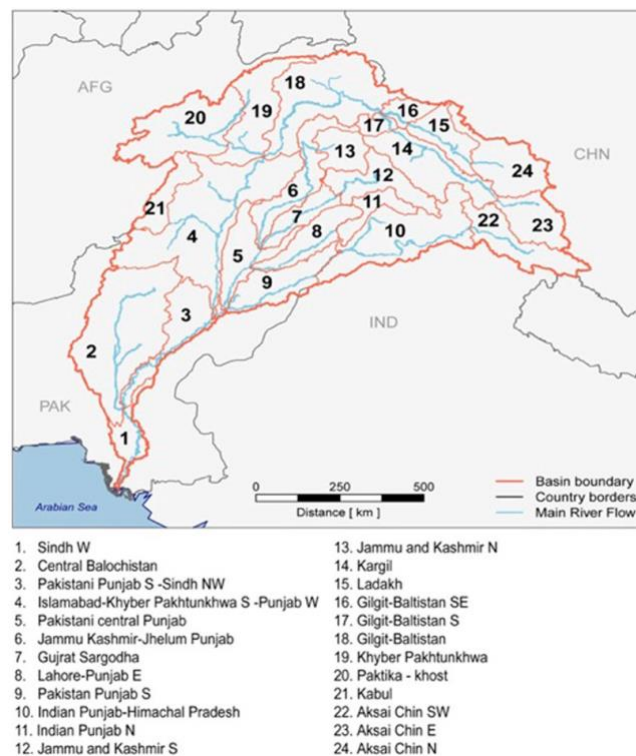


Figure 2.3 Spatial delineation of IRB in the modelling framework

NEST delineates a given study region into a combination of administrative and hydrological units. The administrative units refer to country administrative units, sub-national (administrative) boundaries and the hydrological units refer to sub-basins

(tributaries) here to account for flows within the basin and impacts of upstream water withdrawals on downstream water availability. These two spatial units are intersected using the geospatial technique to create the spatial unit for the modelling framework. The future work will include the further intersection of units to agro-ecological zones to account for more informed agriculture-related decisions. An example of the delineation for the Indus River Basin is depicted in Figure 2.1. A reduced-form river and electricity transmission network enable the optimization of flows and reservoir releases between the spatially distributed units. Crop yields are aggregated nationally to meet projections of future production quotas. The NEST framework includes a hydrological model (CWatM) (Burek et al., 2019) that is linked to the capacity expansion module (MESSAGEix) (Huppmann et al., 2019). The linkage informs the optimization of spatially distributed water resource availability. Socioeconomic and climate data in a gridded format are also harmonized to a common scale and used to define water, energy and crop demands in each delineated management unit.

A high-resolution land-surface (hydrological) model, CWatM (Burek et al., 2019), calibrated to observations that simulate the vertical and horizontal freshwater transfer across terrestrial areas at a daily time scale. Climate impacted water scenarios consistent with the emissions pathways simulated with the global IAM (Integrated Assessment Modelling) are implemented using downscaled climate forcing variables from global climate models. The sectoral analysis is harmonized between both models to capture the historical period and a future time horizon translating demand profiles. CWatM is initially run under baseline conditions to inform MESSAGEix of dynamic constraints on water availability, hydropower potential and irrigation water requirements (Vinca, Parkinson, Byers, et al., 2020). The streamflow values obtained from CWatM are naturalized flows without human activities and water withdrawals since these are obtained from MESSAGEix. These naturalized flows are also used for environmental flow assessments as indicated in Figure 2.2a. Further calibration details are mentioned in supplementary section S2.2.

The resources, technological process and demands are parameterized using data sources mentioned in Supplementary Table S2. Much of the data mentioned in Supplementary Table S2 can be obtained from globally available databases however for some parameters, local data is used to approve the results and calibration of the historical process. The range of uncertainties in the Community Water Model (CWatM) hydrological modelling is covered by using multiple climate models and RCP-SSP

scenario ensembles. The CWatM for the NEST model is calibrated at 5 arcmin resolution using monthly streamflow data during 1995-2010 at Besham station in the upper Indus. Stations at Upper Indus are chosen since it provides both glacial and seasonal snowmelt. The current work includes calibration at a single station: however, future studies will incorporate more observation for improved calibration. The calibration parameter values are indicated in Supplementary Table S3 (Burek, 2019; Vinca, Parkinson, Byers, et al., 2020). The total basin runoff computed from these calibration matches closely with reported data in Laghari et al. (Laghari, Vanham and Rauch, 2012) and Yaseen et al. (Yaseen et al., 2020)

System solutions in NEST include investments in new infrastructure capacity (e.g., power plants, water distribution, irrigation system, and land-use type) to find the least-cost solution by satisfying energy and water demand with supply. It also includes a comparison of different investment types and strategies for water infrastructure technologies, energy systems as well as land use, such as constraining a given level of environmental flow in a river which gives us an integrated solution as an output under global change scenarios. NEST co-optimizes sub-national water, energy, and land system representation over a multi-decadal time horizon. The joint optimization of resource management occurs at the technology level, considering the physical balance between supply and demands from industrial, urban, rural, and agriculture sectors. The basin is disaggregated into 24 sub-national decision-making units representing the intersection between country administrative and sub-basin boundaries (see Figure 2.1 for node IDs). The hydro-economic representation links techno-economic parameters across units with a reduced form river network. For the detailed linkages, mathematical equations, calibration, parameterization and integration of water-energy-food sources and technologies in the modelling framework, refer to the modelling paper by (Vinca, Parkinson, Byers, et al., 2020). The calibration of hydrological & data sources used in the modelling framework is mentioned in supplementary section Table S2 and S3.

2.2.2. Multi-sector transformation pathways

The NEST constrains the flows in the downstream nodes i.e., below Kotri barrage (node1; Figure 2.1) outflowing to the Arabian Sea. However, by constraining the downstream management nodes near the Indus delta, the model allocates EFs and adjusts different EWL technologies as per the available constraints and investments upstream. As mentioned previously, there exists no suitable standard to allocate EFs in

IRB. We gathered the data from local authorities and calculated the average discharge flowing downstream of Kotri barrage historically (1971-2018) (Table S1) and found the average flows reaching Indus delta has been decreasing continuously. Due to the complexity of the basin, we allocated suitable EFs based on the historical flows, the standard defined by the governments, and the standards in the literature in the lower IRB. The choice of percentages of allocation is made on different model runs and analyzing the impacts of water availability in the outflow. This approach suits highly modified and regulated rivers like IRB, where achieving an ecological potential and saving the biodiversity is a target, considering the societal demands for highly modified rivers instead of taking natural flow regime as a reference (Acreman et al., 2014).

The NEST implementation for the IRB has been developed to examine the interplay between regional cooperation and the achievement of multiple targets consistent with the SDGs (Sustainable Development Goals). The analysis in this paper utilizes the model setup and scenario design to explore enhanced ambition for delta EFs (Table 2.1). The baseline scenario optimizes water, energy, and land system costs from 2020 to 2050, with future population and GDP assumptions. The sectoral demand profiles are generated from the Shared Socioeconomic Pathways (SSP2). The system costs include investment and operational costs for all sectors for different nodes and times. The baseline scenario incorporates Sustainable Development Goals (SDG) policies that ensure universal access to piped water and wastewater collection, and decarbonization and electrification of the energy sector in line with the Paris Agreement. These input assumptions and associated data are further summarized in Table 2.1.

Transformation pathways incorporating enhanced EF allocation to the Indus Delta are generated by layering an additional set of constraints on the allowable basin outflow. NEST is used to assess the impacts of environmental flow constraints in the lower Indus for future pathways. The target level is defined relative to the historical outflow levels provided by the local policy as mentioned in Figure 2 (a) and projected with base-year (2015) data. Evidence from the literature shows that historical constraints in the outflow node have not been scientifically tested. The constraints in the outflow node should be tested on-field for a longer period (~10-15 years) to test the biophysical and ecological impacts in the basin. For designing environmental flow scenarios, we designed ecological target-based scenarios, based on the assumption that constraining more water in the southern nodes can potentially increase delta sustainability and improve socio-economic conditions in the Indus delta.

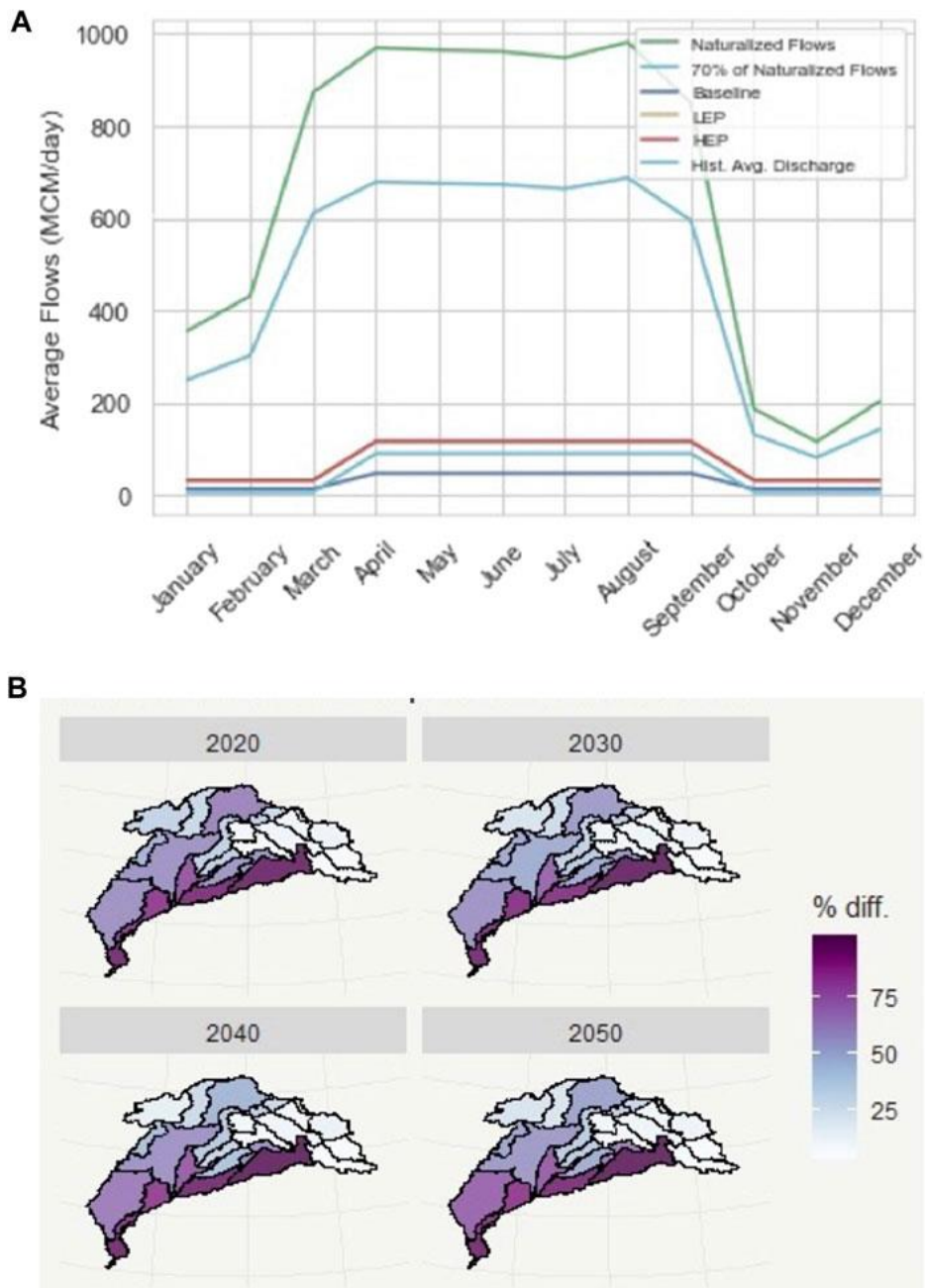


Figure 2.2 (A) Seasonal visualization of average flows per year (MCM/day) incorporated in baseline, historical average discharge downstream for Kotri barrage, EF scenarios and naturalized flows. Scenarios layout and description of sensitivity scenarios (B) A map showing difference between actual flows of baseline scenario and naturalized flows computed from CWATM (Community Water Model) to show percentage variation between both flow types.

Despite the critical role of EFs in Indus Delta sustainability, there is a lack of quantitative analysis linking enhanced EF allocation policies to the adaptation costs borne by upstream sectors. We carried out a parametric model analysis to find the least cost system transformations that support the enhanced allocation of environmental flows in the downstream nodes (i.e., nodes numbers 1, 2, and 3 in figure 2.1).

Constraining the river levels to the naturalized flows (modelled flows without human interaction) results in extreme investment costs. The constraint makes the consumption projections infeasible due to the highly modified nature of the IRB, i.e., much of the existing flow has already been allocated making the shift back to naturalized conditions highly unlikely. Therefore, we allocated EFs such that it generates an economic response function based on a range of EF constraints defined relative to the historical outflow. This provides decision-makers with an understanding of the marginal costs for enhancing EFs. We designed a Low Ecological Potential (LEP) scenario and High Ecological Potential (HEP) scenario by increasing the existing EF ambition levels by 2.5X and 5X, respectively. A visual representation of the flow levels can be seen in Figure 2.2 and its variation across various times during the year. The increased flows during the April-September months are due to glacier melting and the monsoon season in the region. Sensitivity cases are generated to assess the variation in the model results due to uncertainties in the model parameters and policy design. The choice of sensitivities is made based on the domain of research questions, local socio-political issues, and climate mitigation against vulnerability in the region, but do not encompass the full range of uncertainties. The detailed scenario representation and sensitivity details are described in Table 2.1.

Table 2.1 Scenario layout and description of sensitivity scenarios

Scenario	Description	Sensitivity Cases for all scenarios
Common assumptions to all scenarios	Shared Socioeconomic Pathways (SSP) 2 (O'Neill et al., 2017): population and demand projections; Representative Concentration Pathways (RCP) 6.0 (van Vuuren et al., 2011): climate forcing; Indus Water Treaty allocations: planned hydropower projects in 2030, current renewable energy policies, maximum electricity imports fixed to baseline, limited fossil groundwater extraction; flood irrigation being main irrigation technique;>50% of agriculture water withdrawals to historical levels.	
Baseline	Includes baseline policies in the basin, along with the SDG implementation and minimum environmental flow requirement in the outflow node downstream of Kotri barrage	WASTEWTR– Increased wastewater treatment in the systems EMISS – Climate mitigation through the rapid reduction in emissions of Greenhouse Gases (GHGs) by 2050 COOP–Transboundary Cooperation assumes the cooperation between countries AGRI (0.9/1.1) – 10% variation in agriculture demands ELECTR (0.9/1.1) – 10% variation in electricity demands
LEP (Low Ecological Potential)	A low-cost scenario to allocate environmental flows for lower IRB to provide moderate ecological protection against the investment of low-cost technologies by multiplying the historical policy outflow levels by 2.5x (Figure 2.1)	
HEP (High Ecological Potential)	A high-cost scenario that multiplies the historical policy outflow levels by 5x to allocate environmental flows for lower IRB to provide high ecological protection against the investment of high-cost technologies. This scenario assumes high protection of the Indus delta along with the restoration of infertile land with time for improvements of socio-economic conditions.	

2.2.3. Marginal Costs for EF allocation

The marginal costs of EFs allocation help to access costs and opportunities for water, energy, and land systems at a specific instance. The constrained optimization problem solved in NEST generates corresponding Lagrange multipliers representing the marginal change in the objective function value (total system costs) when varying the constraint value by a small amount. In operations planning, the Lagrange multipliers associated with demand constraints are commonly interpreted as the market-clearing commodity prices for recovering system investments. By solving NEST across a range of delta EF constraints, the marginal costs are calculated linking the delta EF allocation level to the cost of implementation. This provides an indicator for the required pricing of environmental flows that recovers the costs of the multi-sector transformation. Importantly, the socioeconomic improvements from delta replenishment are not included. If these benefits exceed the costs, then implementation of the EF policy is an economically net positive. These impacts are complex and highly non-linear. Future work in this area can leverage the marginal costs derived in this paper to compare the economics of implementation. This is like marginal costs used in Marginal Allocation Curves (MAC) for emissions mitigation, where the benefits from avoided adaptation are also excluded. In this case, the marginal cost is therefore calculated as:

$$\begin{aligned}
& \text{marginal cost}_{\text{scenario}_x \text{node}_x} \\
&= \frac{\text{total costs/year}_{\text{scenario}_x \text{node}_x} - \text{total costs/year}_{\text{scenario}_{BAU+SDG} \text{node}_x}}{\text{average EF/year}_{\text{scenario}_x \text{node}_x} - \text{average EF/year}_{\text{scenario}_{BAU+SDG} \text{node}_x}}
\end{aligned} \tag{1}$$

2.3. Results

2.3.1 Total system & marginal costs of EF allocation

The analysis is performed using SDG sustainability targets to offset these costs for EF scenario runs. The SDG constraints in the scenario show additional 10 billion USD/year investments overall across multiple sectors (Supplementary Figure S1(a)). These SDG targets also show additional energy required for water (pumping, desalination, etc.) and lesser water required for energy in SDG targets (Supplementary Figure S2(b)). These costs are already accounted for in the Baseline scenario in the current study. By constraining more water in the enhanced EF scenarios, we see that approx. 28 billion USD (US Dollars) and 103 billion USD per year additional are required across multi-sectors in scenario HEP as compared to LEP, distributed across sectors. Results show that Pakistan must bear all the costs for enhanced EF allocation in the lower IRB. The costs here refer to the sum of operational and investment costs from a systems perspective.

Marginal costs for EF allocation (as discussed in section 2.3) depict the marginal costs (billion USD/MCM) of EF scenarios compared to the baseline scenario. The costs are aggregated costs for all time horizons and all spatial regions, with future cash flows discounted at an average rate of 7%. 3.78 and 5.44 billion USD/MCM is required in LEP & HEP scenario for the whole river basin. The lower IRB and regions where most of the storage reservoirs are available in IRB shows comparatively higher in number, has increased marginal costs than other regions. This shows that the lower Indus must bear most of the EF allocation-related costs. The regions in the basin including storage reservoirs also have higher marginal costs which show the dependency of EFs on storage reservoirs. The marginal costs are calculated here as pricing of EF allocation increases rapidly by moving to a higher ecological target for the Indus delta. The economic implications of this pricing are beyond the scope of this paper and will be studied in future work.

Results show the need for investments in water distribution sectors due to the increased allocation of EFs downstream. Optimizing and improving water distribution is critical for EF allocation. Water distribution includes diversion, canal, desalination, and wastewater treatment. The increased investment in water distribution also shows that proper integrated water management can enhance EF allocation. Wastewater treatment and allocation are critical for the provision of EFs in the river basin. Although a specific wastewater treatment ratio is incorporated as part of the SDG6 targets, results show that water withdrawals in the region require more investment in the wastewater treatment sector. Increased wastewater treatment not only helps increase the flows in the system but also helps ensure the water quality parameters in the river basin which is also often neglected in the case of IRB studies. To analyze the wastewater aspect more, we analyzed the EF scenarios with increased wastewater treatment ratio in the sensitivity analysis (see Table S1 in supplementary data for cost comparison). The results show that an additional 5-50 billion USD/yr. across scenarios is required for improved water quality parameters.

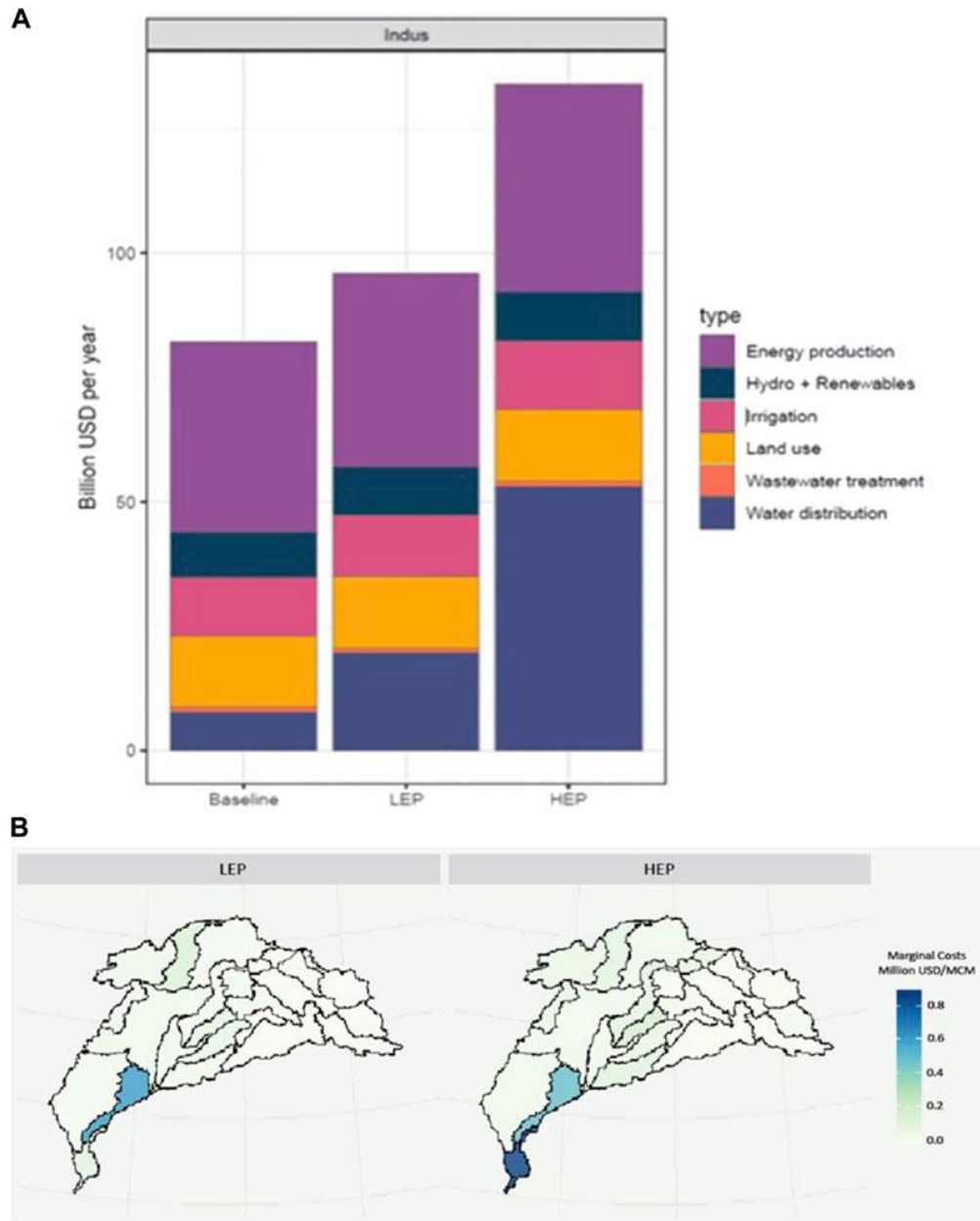


Figure 2.3: Average system costs (investment and operational) per year from optimization model for (A) EF scenarios and (costs are indicated in USD2010 values) (B) regional marginal costs showing the regions with increase in marginals in IRB per allocation of EF in downstream nodes. During the post-processing phase, each energy, water, and land technologies are grouped into clusters for displaying aggregated results. The technological clusters from Figure 2.3 (A) include coal, oil, electricity import in energy production; river, canal, existing and planned hydropower projects, and renewables (solar and wind) in Hydro+RES; diversion, distribution, wastewater collection, desalination, and canal infrastructure costs in water distribution; irrigation technologies (flood, drip, sprinkler, and canals) in Irrigation; crop production and biomass costs in Land use.

2.3.2 Least-cost structural changes in the Energy-Water-Land (EWL) sectors

The optimization model not only shows the system costs but also system transformations in terms of additional capacity, shifts in water sources, energy supply and the interactions between water, energy, and land systems. We see that average water use per year reduces in the EF scenarios from the baseline scenario, however, a major portion of water is being allocated for flood irrigation. Due to the agriculture dependency of the system, floor irrigation has been widely used which is a highly water consumptive irrigation type. The current study motivates further research into exploring shifts to smart irrigation technologies for a sustainable river basin. The share of groundwater in the water source increases rapidly from 43%-50% in the baseline scenario to 59-63% in LEP and 64-66% in the HEP scenario. This shows that while allocating environmental flows downstream of IRB, the groundwater resource is stressed due to high demands and withdrawals. The share of oil in the electricity supply by source (Figure 2.4 (b)) increases in the higher EF scenario, which is not sustainable in terms of the climate vulnerability of the river basin in the future. However, considering a climate mitigation scenario (EMISS) can help to address a more sustainable option for climate mitigation along with river sustainability.

The nexus interactions show that due to increased allocation of water downstream of IRB, we need more energy for water withdrawals and irrigation which also increases water use for power plants cooling. This includes investments in desalination plants causing the system to consume more energy as compared to surface runoff. The energy system transforms towards less water consumptive technologies to save water for EF allocation.

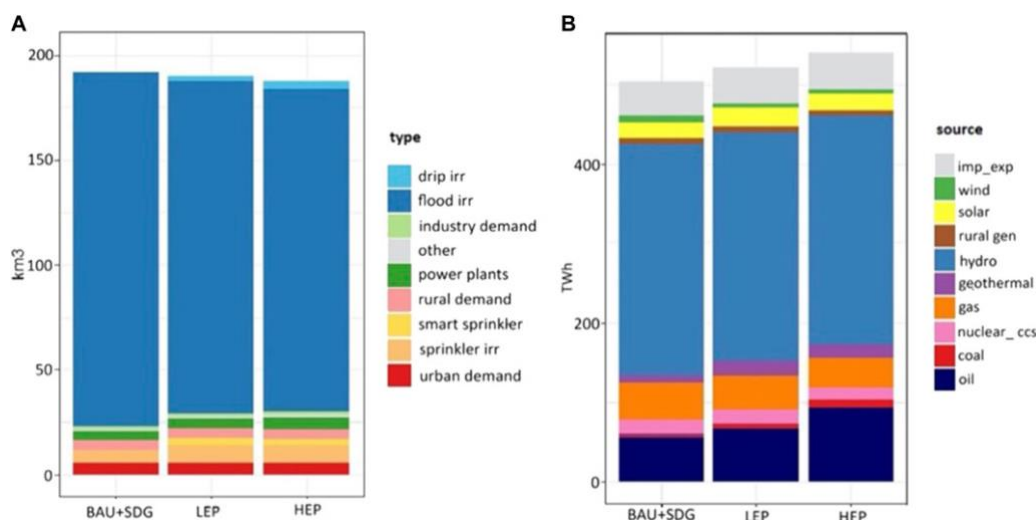


Figure 2.4 (A) Average water use per year for different sectors **(B)** Electricity supply by source per year for EF scenarios / Water use for different sectors and electricity supply for various sources represent nexus interactions.

2.3.3 Sensitivity & Uncertainty

Results from sensitivity cases include the variation in agriculture and electricity demands, transboundary cooperation, increased wastewater treatment, rapid reduction in emissions across the EF scenarios (see Table S4 for Supplementary details). Results show that variation in electricity and agriculture demands significantly impact the savings from baseline cases from 2-25 %. This represents increased dependency on agricultural systems in the river basin. Since the energy system is also dependent on water in the form of hydro energy potential and cooling water for power plants, the costs vary with electricity demand variation in the system. Also the increase in costs in the irrigation sector in the EMISS scenario depicts that shifts to low water and energy consumptive irrigation technologies are key for climate mitigation in the future years. The rapid reduction in emissions under the decarbonization policy and shift towards low-carbon technologies results in a cost increase in water distribution, renewables, and irrigation. However, when trade barriers are relaxed in the transboundary cooperation scenario (COOP), the average system costs per year significantly reduce in the LEP & HEP scenarios. This is because there are significant opportunities for irrigation water efficiency in the Indian portion of the river basin, and these investments increase the amount of flow that transfers into Pakistan and drain into the Indus delta.

Additional uncertainties in the analysis and not covered by the scenario setup include the influence of future climate extremes on water availability and flood management in

the IRB. There is also a need to meet EF guidelines in all basin tributaries and for groundwater systems, but these spatially distributed EF constraints were not considered. These aspects create additional management challenges and are expected to increase the cost of securing EFs in the delta region.

2.4. Discussion

The study assesses the role of freshwater provision in the downstream of the IRB and its importance for the replenishment of the delta. It uses an engineering economic optimization framework to assess the prices, impacts and structural shifts required within the water, energy, land systems of the IRB. Based on the historical flows reaching Indus delta, the standard defined by the policy makers, and the model responses for water allocation in the upstream, we identify optimal flows that forms a narrative for the environmental flow requirements for the lower IRB and thus could potentially help to replenish the Indus delta. From the results, we found out that the delta flows can be improved in the model by 1) investing in water efficiency measures in the irrigation, water treatment, conveyance, and power plant cooling sectors; and 2) investing in alternative supply-side measures including extraction from groundwater resources, advanced water treatment and new conveyance canals. The allowable flow constraints are implemented from 2030 onwards in the model to reflect the SDG timeline. The flow constraints are varied over a range of ambition levels to provide an indicator of marginal cost implications and the value of delta flows derived from an infrastructure investment perspective.

Allocation of environmental flows to replenish the Indus delta using a designer approach causes an increase in system costs from 17-32% in LEP to 68-72% in the HEP scenario across multiple sectors from the baseline scenario. We propose that the system cost representation for EF scenarios and sensitivities can help to determine the scale of investments across different uncertainties for policymakers and river planners aiming to assess the level at which the allocation of EFs can be achieved in the future. Although investments increase as more water is allocated for EFs downstream, these EFs protect the Indus delta from serious long-term ecological threats. Thus, some trade-offs need to be considered by regional planners to find the right balance between EF allocation and financial sustainability. This study provides river planners with insights into the scale of costs for water, energy and land sectors and which technologies in the system can be leveraged together to replenish the delta in a least-cost way.

The linkage between the upper and lower Indus and a better understanding of extreme climate change impacts, impacts on water, energy and land resources are complex in the IRB (Shrestha et al., 2021). The significant climate variation from the high altitude snow-capped to the sub-tropical climates in the lower IRB makes IRB extremely sensitive to climate change variability (Krishnan et al., 2019). EFs allocation in IRB is dependent on the surface water availability from the upper Indus as mentioned in previous sections, whereas dependence of surface water in IRB on glacial meltwater and snowmelt poses dire consequences on surface water availability (Lutz et al., 2019). Due to higher glacial melt, the river flow will increase causes more frequent flooding and droughts which poses threats to river sustainability in the future.

Although the main discussion is around the EF scenarios which ensure increased water availability in the downstream regions, we propose to explore sensitivity cases presented in this paper for further studies and policy analysis such as increased wastewater treatment can help not only increase water availability but also enhance water quality aspect or climate mitigation scenario for the reduced emissions target by mid-century.

2.5. Conclusion

Evidence from multiple literature studies show that the Indus delta ecosystem has experienced losses in fisheries, economical gains, mangroves due to human induced stressors in the past years. Also it has been observed in studies that decrease in the freshwater reaching to delta and sediments are one of the major causes of the damage of Indus delta (Salik et al., 2015, 2016; Kidwai et al., 2016, 2019). This study assesses the multi sectoral impacts of provision of freshwater to Indus delta and associated costs in the water, energy, and land sectors. This study also lay out the need for defining the environmental flow requirements within the basin and its importance for replenishing the Indus delta. A standard for environmental flows is yet to be defined by basin practitioners in the IRB and a detailed eco-hydrological study is needed to determine the ecosystem response to the EF policies. The delta EF constraints could cause stress on groundwater resources in the river system if groundwater is used to mitigate surface water withdrawals in response to EF policies. EF standards need to consider a sound groundwater withdrawal rate for ecological protection (Gleeson and Richter, 2018; Driver et al., 2020). Moreover, hydropower energy generation decreases when a higher EF target is achieved in the system, which increases energy costs at the user-end. River

basins that have the potential for storage expansion might be able to reduce these interactions by modifying the flow pattern. Ruan et al. (Ruan, Wang and Cao, 2021) mention a similar conflict of hydropower projects and impacts on environmental flows using a case study from China. Hydropower expansion plans in the upper IRB raise concerns for downstream water availability and have implications on socio-economic conditions near the Indus delta. Dhaubanjari et al. (Dhaubanjari et al., 2021) developed a systematic framework for the sustainable assessment of hydropower potential in the IRB. We propose that future studies on environmental flows may explore the synergies and trade-offs between hydropower expansion in the upper IRB and the impacts on hydrological and socioeconomics in the lower IRB. The multi-sector, multi-scale modelling framework leveraged in this paper can support this type of analysis and will be the topic of future research. EF allocation in IRB is crucial for ecosystem sustainability and deltaic protection. The current policy structure of water allocation lacks scientific evidence for EFs. Keeping the competing water uses in agriculture, municipal, industry, energy, and ecosystem services, it is critical for stakeholders to build a consensus on the allocation of water for EFs. This study accesses the EF requirements based on the integrated impacts on EWL sectors using an innovative approach by repetitive model runs to see the impacts of the hydrological and socio-economic condition in the Upper Indus in Lower Indus. However, we think that implementing EF in IRB requires adaptive management techniques i.e., learning by doing approach. The stakeholders need to negotiate the objectives and outcomes of the EFs allocations for the river basin sustainability. Also, the integrated impacts of EF allocation provided critical choices in the nexus, including over infrastructure such as dams, managing abstractions for irrigation and allocation of water for ecosystems. With this study, we propose that there is a need for more focused and on-site experiments to develop environmental flow standards. These are critical for the vulnerability of IRB to climate change impacts, and it will help the IRB to adapt to rapidly changing and uncertain climate in the basin. The 1991 Water Apportionment Accord for sharing water among different provinces is ambiguous and requires clear interpretation to allow fair water allocation in the downstream of IRB for the socio-economic well-being and replenishment of delta.

Data Availability Statement

The datasets and the model used for this study can be found in the NEST GitHub Repository (<https://github.com/iiasa/NEST>).

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Chapter 3 MESSAGEix-GLOBIOM Nexus Module: Integrating water sector and climate impacts²

Preamble. The Integrated Assessment Model (IAM) MESSAGEix-GLOBIOM developed by IIASA is widely used to analyze global change and socioeconomic development scenarios within the energy and land systems across different scales. However, until now, the representation of impacts from climate impacts and water systems within the IAM has been limited. We present a new nexus module for MESSAGEix-GLOBIOM that improves the representation of climate impacts and enables the analysis of interactions between population, economic growth, energy, land, and water resources in a dynamic system. The module uses a spatially resolved representation of water systems to retain hydrological information without compromising computational feasibility. It maps simplified water availability and key infrastructure assumptions with the energy and land systems. The results of this study inform on the transformation pathways required under climate change impacts and mitigation scenarios. The pathways include multi-sectoral indicators highlighting the importance of water as a constraint in energy and land-use decisions and the implications of global responses to limited water availability from various sources, suggesting possible shifts in the energy and land sectors.

² This chapter have been submitted to Geoscientific Model Development and it is under review. The preprint is available at <https://egusphere.copernicus.org/preprints/2023/egusphere-2023-258/>

3.1 Introduction

Multiple inter-sectoral objectives, including economic, environmental, and social goals, are integrated into formulating effective, sustainable policies over the long term. Nexus approaches have been increasingly used and considered in policy analysis, including the Sustainable Development Goals (SDGs), to exploit synergies and avoid negative trade-offs and unintended consequences in light of the increased awareness of the interdependencies between the energy, water, and land sectors (EWL). Climate policy assessment helps identify pathways that can help achieve the 'well below 2°C' global warming target and other SDGs, such as access to clean energy, water and sanitation, and food security (Khan et al., 2017, 2018; S. Parkinson et al., 2019a; S. C. Parkinson et al., 2018). In addition to climate change risks, limited resources compounded by population and GDP growth pose an additional challenge. (Byers et al., 2018). Integrated Assessment Models (IAMs) help researchers and policymakers understand the long-term consequences of unequal socioeconomic development and climate change scenarios. These scenarios are widely used for accessing the cost and benefits of climate change impacts and mitigation strategies. These models integrate sectors (global economy, energy, water, agriculture, and forestry) to provide policy insights relevant to climate change scenarios (Weyant, 2017). IAMs provide long-term transformation pathways to answer critical questions on climate change transition to ambitious climate policy goals (Riahi et al., 2017).

Substantial efforts have been made in developing scenarios informing a range of futures with varying societal and socioeconomic assumptions. (Riahi et al., 2017b). The most used set of scenarios in IAMs includes the Shared-Socio-economic Pathways (SSPs), a group of five quantified narratives for the evolution of socioeconomic development globally for the 21st century (O'Neill et al., 2017), and the Representation Concentration Pathways (RCPs), a set of four scenarios spanning a range of radiative forcing values (D. P. van Vuuren et al., 2011). These narratives have been translated into assumptions for economic growth, population change, and urbanization to analyze baseline and climate mitigation scenarios (Riahi et al., 2017b).

Although SSPs were designed to analyze the challenges for mitigation and climate adaptation, integration of climate impacts and adaptation of energy and land sectors to water sector constraints has, until recently, been limited in the IAM scenarios due to substantial challenges in technical implementation and representation of climate impacts. Long-term assessment of climate mitigation scenarios often neglects the

climate impacts on system performance, resulting in avoiding adaptation costs in the analysis (Calvin et al., 2013; Piontek et al., 2021b). Many IAMs often consider the costs of resources in an aggregated spatial region/continent. In the case of an adaptation, the key element for change is required from a local/national scale. More detailed information on the spatial distribution of costs and benefits of impacts and adaptation is required to inform adaptation actions and policies (Patt et al., 2010).

Impact modeling activities across diverse modeling groups, such as the Intercomparison Model project (ISIMIP) (Frieler et al., 2017), have been conducted to understand the impacts of climate change better individually. These sectoral exercises include assessments of changing yields, runoff changes, food production, and groundwater estimate that economic impacts have been estimated using a variety of methodologies, depending on the types of impacts considered, such as the relationship between climate damages and temperature (Dellink et al., 2019). Some studies have empirically linked climate conditions with socioeconomic systems and incorporated distributional factors into cost-benefit models, resulting in increased social costs of carbon and more stringent mitigation pathways (Diaz & Moore, 2017; Hänsel et al., 2020; Howard & Sterner, 2017; Kalkuhl & Wenz, 2020; Moore & Diaz, 2015). It is becoming quite evident to have the representation of biophysical climate impacts into integrated assessment models to comprehend the effects of different sectors on the techno-economic outlook and to determine mitigation and adaptation pathways (Hausfather et al., 2022; Köberle et al., 2021). (Piontek et al., 2021a) analyzed the economic impacts of climate change using the REMIND IAM model, but biophysical climate impacts were not represented. (Soergel, Kriegler, Bodirsky, et al., 2021; Soergel, Kriegler, Weindl, et al., 2021) emphasized the significance of considering the consequences of climate impacts and evaluating how integrated scenarios respond to these impacts, especially regarding sustainable development pathways.

New analytical approaches and solutions are required to address the challenges of impact and adaptation in long-term policy analysis (Patt et al., 2010; Riahi et al., 2017b; X. Wang et al., 2016). The regional inequality of climate impacts' exposure can also be considered by introducing climate impacts in the development trajectories, such as the SSP framework (Taconet et al., 2020). There is a need for a balanced synthesis of Shared Socio-economic Pathways (SSP) narratives with climate impacts, adaptation, and resilience pathways to assess water, food, and energy security to access sectoral adaptation costs and impacts (Rasul, 2016; Schleussner et al., 2021). Regions highly

exposed to climate impacts, highly vulnerable populations (Byers et al., 2018), and developing regions face the biggest challenge in adapting to climate change impacts and meeting population-driven demands in the EWL sectors (Rasul & Sharma, 2016a). Integrating cross-sectoral Energy Water Land nexus analysis in IAMs can help identify trade-offs and synergies, integrate policy implementations, and address equity dimensions, such as the population exposed to hunger or lacking access to sanitation and electricity. This holistic approach enhances the resilience of communities and promotes sustainable development. This study addresses these gaps by proposing a framework that integrates climate impacts, strengthens the water sector (which is essential in the context of climate change), and formulates scenarios in conjunction with sustainable development assumptions to assess the impacts of climate change under mitigation, adaptation, and sustainable development pathways.

Due to hydrological data's spatial and temporal complexity, it is challenging to translate hydrological information into the IAMs. Usually, the spatial extent of IAMs is macro-regions, and the aggregated hydrological information loses adequate information at a macro-level. There is always a need to find a middle ground between showing the hydrological process more accurately and lowering the cost of computing (Fricko et al., 2016; S. Parkinson et al., 2019a). There have been efforts to link a higher spatial resolution water sector to account for hydrological balance and constraints in IAMs, such as (Yates, 1997) and (Kim et al., 2016).

This paper introduces a new module of the global MESSAGEix-GLOBIOM framework (Krey et al., 2016; Riahi et al., 2021). The nexus module attempts to fill the gap in integrated assessments by improving the representation of biophysical climate impacts across the Energy, Water Land (EWL) sectors and enhancing the water sector representation. We develop scenarios that can effectively capture climate impacts across multiple sectors using this module. Then these scenarios are combined with SDG targets in EWL sectors to capture the synergies and trade-offs of climate impacts and sustainable development pathways. The manuscript is structured as follows: Section 2 comprehensively explains the model's structure, improvements, and modular procedures, with detail on specific components of the model, such as the water sector, biophysical climate impacts, Sustainable Development Goals, and flexibility at different scales (with Zambia as an example), described in section 3. Section 4 presents

the results as the model's ability to answer different research questions, and Section 5 concludes with a summary of the study's significant findings and contributions.

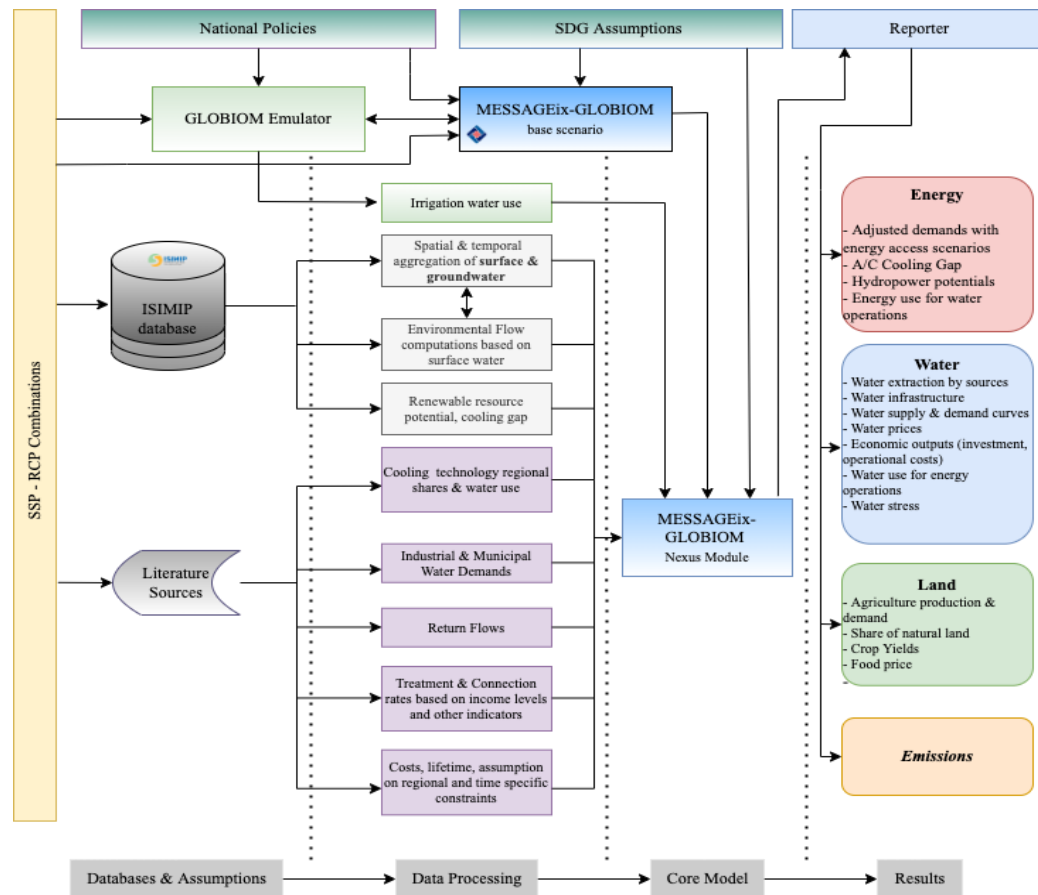


Figure 3.1 Structure & data flows of MESSAGEix-GLOBIOM Nexus Module. SSP-RCP combinations of scenarios are used as basis for development of nexus module. The module is built on the typical MESSAGEix-GLOBIOM scenario. The typical scenario has updated biophysical climate impacts in the energy and land sectors and then the water system is added. The database assumptions, structure and processing are the main components of this study besides the core model. Using the computational tools and post-processing methods, multi-dimensional sectoral results inform the pathways for different scenarios.

3.2. Model structure & workflows

Least-cost optimization using engineering-economic modeling is a common approach for long-term energy, water, and land planning (Barbier, 2012; Khan et al., 2017). However, it is not typically performed in a holistic manner that jointly considers system solutions across sectors in a single algorithm. These approaches have been a vital component of the MESSAGEix framework in analyzing sustainable transition in climate change mitigation and sustainable socioeconomic development (Huppmann et al., 2019; Khan et al., 2018). Engineering-economic modeling methods to quantify impacts and resource potential, and costs across different spatial and temporal scales are employed within the nexus module. The approach is both engineering and economical in scope because it combines physically based models of infrastructure

systems with cost functions and decision rules for operation, expansion, and retirement at the process level through time. The theoretical underpinning of decision modeling is that system design choices are made at least cost over the planning horizon in a perfect foresight, integrated way. The end-use prices for consumers are minimized, and flexibilities across sectors to absorb sectoral trade-offs are fully utilized and planned for in advance.

The "nexus" module of the MESSAGEix-GLOBIOM framework, MESSAGEix-GLOBIOM Nexus v1 presented in this paper, contains endogenous spatially- and temporally explicit climate impact constraints and water allocation algorithms. This module extends the foundational work conducted by (S. Parkinson et al., 2019a) and addresses the gaps in the previous study by improving the water sector resolution, water constraints, and climate impacts. The module here refers to expanding the core global framework to represent specific dimensions straightforwardly at the cost of increased computational complexity and cost. The MESSAGEix-GLOBIOM Integrated Assessment framework is a global energy-economic-agricultural-land use model that evaluates the interconnected global energy systems, agriculture, land use, climate, and the economy. Using the Linear Programming approach, the MESSAGEix framework optimizes the total discounted system costs across all energy, land-use, and water sector representations. It provides options for both perfect foresight and recursive-dynamic modes. Its adaptability and flexibility make it a powerful instrument for optimizing transformation pathways at various scales, emphasizing minimizing system costs. It comprises five complementary models or modules: the energy model MESSAGEix (Huppmann et al., 2019), the land use model GLOBIOM (Havlík et al., 2014), the air pollution and greenhouse gas (GHG) model GAINS, the aggregated macro-economic model MACRO, and the simple climate model MAGICC (Meinshausen et al., 2011). The framework combines the MESSAGEix and GLOBIOM models to assess and model policy scenarios' economic, social, and environmental implications. The framework comprehensively examines the trade-offs and synergies between various policy objectives, such as reducing greenhouse gas emissions, boosting food security, and safeguarding natural resources. To access sustainable development targets, the framework is utilized to evaluate the feasibility and implications of alternative policy choices and to guide decision-making.

The nexus module simultaneously determines energy portfolio, land use, and associated water requirements, and feedback from constrained resources, such as

limited water availability for energy and land use resource usage. It includes a framework for connecting information from hydrological models. It is designed to adapt any Global Hydrological Model (GHM) output and be flexible across different spatial scales (regional definitions, global and country scales). A higher-resolution spatial layer at the basin scale is embedded within the module to retain valuable hydrological data. The information from the water sector is then mapped to the global MESSAGEix energy system at MESSAGEix native region level. This enables converting valuable water resource data to the energy sectors and vice versa. The framework balances basin-level water availability and demand while mapping water necessary for energy and land usage at the MESSAGE native region level. The nexus module tracks annual municipal and industrial water demand, water required for power plant cooling technologies, energy extraction, and irrigation water use, balancing through water supply from different sources, such as surface water, groundwater, and desalinated water.

Furthermore, a wastewater treatment infrastructure representation tracks the water during collection, treatment, and reuse. Water demands are tracked across urban and rural components to enable a more comprehensive understanding of future development and adaptation pathways. Additionally, biophysical climate impacts are integrated across EWL sectors, including water availability, desalination potential, hydropower potential, air-conditioning cooling demand, power plant cooling potential, and land-use variables (bioenergy, irrigation water) to account for the feedback associated with climate change within the model. GLOBIOM was also adjusted to capture water supply, availability, scarcity, and demand from other sectors based on the hydrological data of GHM under different climate-forcing scenarios. In this case, GLOBIOM and the MESSAGEix nexus module are configured to use outputs from gridded GHMs from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) (Frieler et al., 2017). This information is specified for 210 river basins based on the Hydro SHEDS basin delineation (Lehner et al., 2006) (Figure 3).

One of the critical features of the Nexus module is its ability to simulate global interactions across multiple sectors and systems. It allows the model to represent the complex feedback and spillover effects from policy interventions, such as the potential implications of land use changes on the global food system and the energy sector or the water footprints of the energy system. The framework allows a realistic and complete study of policy possibilities by incorporating many facts and hypotheses, such as

population and economic growth predictions, technology advancement, and resource restrictions. The integrated approach thoroughly considers the trade-offs and synergies between diverse policy objectives, such as reducing greenhouse gas emissions, enhancing food security, and protecting natural resources. Considering biophysical climate impacts across different sectors helps to access different adaptation needs and responses in different sectoral outputs across different pathways. In the context of sustainable development, it can analyze the viability and implications of various policy alternatives and inform decision-making.

The MESSAGEix-GLOBIOM framework allows flexible integration with different modules, such as those on water, transport, materials, and buildings. The development process of the nexus module is divided into four phases: (i) identifying databases and literature studies for key assumptions; (ii) data processing to make the data model compatible; (iii) setting the core module, which compiles the data and populates it into the core model; and (iv) post-computing of the model outputs to provide ready-to-use results in a database and for visualization tools such as scenario explorer (Huppmann et al., 2018).

The module uses SSP-RCP (Shared Socioeconomic Pathways – Representative Concentration Pathway) combinations as narratives for creating a baseline scenario. Each scenario is developed using SSP-RCP combinations, national policies, and Sustainable Development Goal (SDG) assumptions aggregated at the R11 region. National policies, including energy use and emission trajectories, are formulated based on the existing MESSAGE(Balkovič et al., 2014) at a 0.5° x 0.5° spatial resolution, distributed monthly over the growing season based on local cropping calendars for a 10-year time step. These requirements are used as input to the GLOBIOM model. We used the ISIMIP database (Frieler et al., 2017) and Global Hydrological Models (GHMs) outputs for water availability and hydropower potentials for biophysical impact indicators. The GLOBIOM model upscales these water requirements and provides irrigation requirements at an aggregated 37 regions based on land-use allocation decisions.

A typical scenario from the MESSAGEix-GLOBIOM is used to develop and extend the nexus module and consists of several crucial components (Riahi et al., 2021). Socioeconomic assumptions on population and GDP are used to form energy demand projections. Nationally Determined Contributions (NDCs) are applied to various sectors and configurations as policy implications, including but not limited to emission targets, energy shares, capacity or generation targets, and macro-economic targets. The reference energy system in this scenario features a comprehensive set of energy resources and conversion technologies from extraction to transmission and distribution. This scenario's outcome estimates technology-specific multi-sector responses and pathways for various sectoral targets. The analysis is based on the Shared Socioeconomic Pathway (SSP) 2, which builds on historical trends as the starting point. The time horizon for the optimization framework of MESSAGEix-GLOBIOM extends from 2020 to 2100, with a non-regular distribution of time steps.

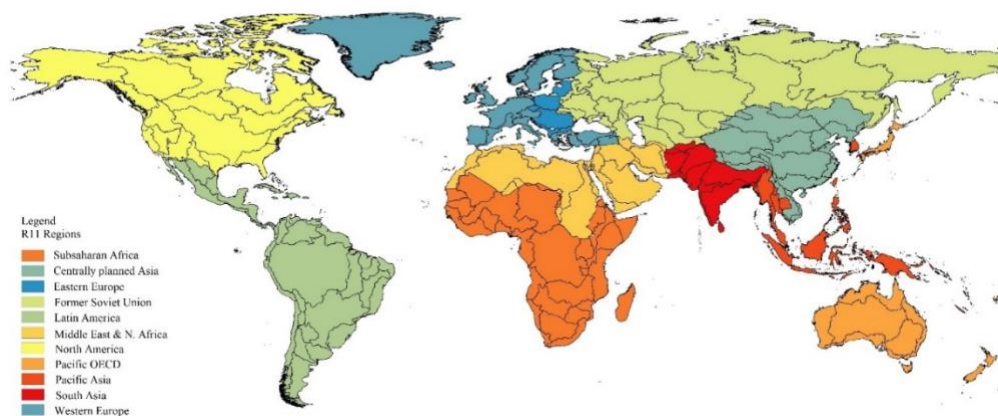


Figure 3.2 Delineation of basins within the MESSAGE R11 regions. The HydroSHEDs basin level 3 is intersected with MESSAGE R11 regional delineation, and the new polygon are used as decision units in the water sector. The distinct colors in the maps represent R11 regions however polygons inside each distinct colored R11 regions are the B210 basins intersected by R11 region. The complete list of basin names along with the area in km² can be looked in the GitHub repository ([data/node/B210_R11.yaml](#))

Further information on the typical scenarios of MESSAGEix-GLOBIOM can be found in the technical documentation (Krey et al., 2016). The scenario is further extended from the typical scenario in the nexus module using specific policy and technological assumptions. The configuration can manage any SSP-RCP combinations to access a diverse range of pathways compared to each other and the Reference scenario.

3.3 Water, Climate, and SDG implementation and results. The subsequent sections explain the modeling framework's water resource structure (supply, demand, and infrastructure) (Section 3.1), and Sections 3.2 and 3.3 discuss

integrating biophysical climate impacts and SDG-related assumptions within the model.

3.3.1 Water resources and the water sector

The reference system for the water sector in the nexus module of MESSAGEix-GLOBIOM is shown in Figure 3. This study represents the MESSAGEix-GLOBIOM (energy system model) in native R11 global macro-regions via its energy and land systems. The data sources used across the water sector are detailed in Table 3.1. The water sector loses important spatial information if aggregated on a macro scale. As a first step toward balancing water demand and supply, we have selected the Hydro SHED River Basin Level 3 (Lehner et al., 2006) intersected with the R11 region and annual timestep as the ideal standard scale. This spatial layer results in 210 basins (B210, see Figure 3.2), providing a more powerful depiction of the supply-demand system (Figure 3.2). The energy demand for water uses and water withdrawals for irrigation and thermal power plant cooling is mapped from B210 to R11. This allows for balancing water supply and demand estimates at a suitable scale where the economic decision incorporates information on all processes, including water availability. We acknowledge that aggregating water needs across vast regions may underestimate the cascading effect of binding water limitations at the local level and the local level adaptation components. Using further high-resolution basin definitions adds additional complexity to the model due to upstream and downstream interdependence. Our initial effort identifies the primary long-term regional and global drivers of gross imbalances in the supply and demand for water resources. Our ongoing research focuses on determining the most appropriate geographical (grid, sub-basin, or basin) and temporal (daily, monthly, or annual) scales for reconciling water demands and supplies in the global IAM for more robust climate extremes and adaptation needs. To better understand the spatial distribution and water balance of regions, we can look at the Nile River basin, which extends across South Africa and the Middle East (R11 native regions). Due to the overlapping of these two R11 regions, we come up with two distinct spatial units: Nile-Middle East and Nile-South Africa. Now for Nile-South Africa, using proxy indicators such as basin area and the proportion of available water in each basin, we calculate the proportion of renewable water resources available from the Nile and the total water availability in the South African region. This 'downscaled' value

plays a crucial role in the model, allowing us to reconcile the available water supply options with the region's varying water demands.

The water balance in the water sector of the IAM is

$$Fr_{B,t} + Gw_{B,t} + FGw_{B,t} + Ww_{B,t} + D_{B,t} \geq Mc_{B,t} + (Irr_{B,t} + Ew_{B,t}) + Ef_{n,t} \quad (1)$$

$$(Irr_{B,t} + Ew_{B,t}) \leq \sum (Irr_{R,t} + Ew_{R,t}) \times share_B \quad (2)$$

Where Fr is the surface freshwater supplied from the river basin, Gw is freshwater supplied from groundwater aquifers, FGw is the non-renewable groundwater extractions, Ww is treated water provided from wastewater recycling facilities, D is desalinated water, Mc represents municipal and industrial sectoral demands, Irr defines the irrigation water withdrawals from the GLOBIOM emulator, Ew is the water demand for the energy system. Irrigation and energy water demands are balanced at the regional level, and Ef is Environmental flows calculated using Variable Monthly Flow (VMF) method (Supplementary Figure S2.1.3) (Pastor et al., 2014a) R represents MESSAGE energy regions. In contrast, B represents river basins within the given MESSAGE regions, and t is time periods at a 5-year annual time interval. $share$ is the share of freshwater in basins (B) per each region (R) used as a proxy to balance irrigation and energy demands at the basin (B). All the values are in km³/yr. In GLOBIOM, irrigation water withdrawals are treated as residual claimants, with the water demands for municipal and energy taking priority (Frank et al., 2021a; Palazzo et al., 2019). The water withdrawals are balanced with the supply of each model decision-making period and region.

Within the model, the choice between the supply system is motivated by the associated investments and operational costs. Renewable surface and groundwater freshwater are prioritized based on the cost. The other priority choice of supply between wastewater reuse, desalination, and fossil groundwater varies across regions and the available potential in each region. On the supply side, we use global gridded runoff and groundwater recharge data from the Community Water Model (CWatM) (Burek et al., 2019) and GHM outputs from ISIMIP (Frieler et al., 2017) Three bias-corrected meteorological forcing data driving from different climate models (GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR) are used to estimate surface runoff and groundwater recharge. We use multi-model ensemble mean runoff and groundwater recharge as an available renewable freshwater resource. We aggregate the gridded data (0.5° X 0.5° spatial, daily timestep) onto the B210 basins and 5-year annual average. For spatial

aggregation, the spatial sum is used to sum the grid hydrological outputs (runoff and groundwater recharge) to the B210 basins. The detailed process has been summarized in Supplementary Table S2.

We apply a quantile approach with monthly freshwater (surface and groundwater) resources for temporal aggregation to incorporate hydro-climate variability and prolonged dry periods. For example, for the 10th percentile, the monthly mean is first calculated from daily data. Then we use the 10th percentile (Q90) of monthly freshwater runoff for a 20-year rolling window to determine a reliable flow for 90% of the time. This type of percentile methodology applied to multi-decadal periods is frequently used in water resource and environmental flow assessments (Gleeson & Richter, 2018; Prudhomme et al., 2014; Satoh et al., 2022) to account for the seasonal low flows experienced in typical wet and average years, although not the driest 10% of months (over 20 years). Figure S2.1 B shows the Q90 flows overlaid on the monthly flow data for the significant basins to show their reliable flows. We have run the scenarios for evaluating the model's sensitivity based on the flow quantiles.

We used the approach followed by (Graham et al., 2020) to calculate the municipal water demands. Urban and rural components of municipal water demand projections are calculated using gridded population and income-level projections data (T. Wang & Sun, 2022). Manufacturing demands are generated following a similar approach used by (Hejazi et al., 2014). Historical country-level data for 2015 is estimated by subtracting energy sector withdrawals from total industrial sector withdrawals. Future changes in manufacturing demands are projected, assuming convergence towards a log-linear model between GDP and manufacturing withdrawals. Demands are distributed across countries based on growth in GDP and then downscaled to 7.5 arcminutes and re-aggregated at the B210 basins. Supplementary Figure S shows urban and rural components of municipal demands and industrial demands for 2050, whereas the data is provided in the GitHub repository (See Data Availability). Supplementary Figures S3.1 & S3.2 shows average municipal and industrial demands across the basins.

The wastewater treatment system is adapted and improved from the previous implementation by (Parkinson et al., 2019). Figure 3.3 shows the framework's conversion steps from wastewater collection to wastewater reuse. The model includes two generalized urban wastewater treatment technologies to simplify the number of decision variables. The first represents a standard secondary-level treatment facility

commonly found in a mid-sized city. In contrast, the second includes recycling capabilities and is parameterized to represent a standard facility suitable for upgrading municipal or manufacturing wastewater to potable standards, such as a membrane bioreactor. In addition, the model includes a rural wastewater treatment technology that meets the United Nations' guidelines for clean water and sanitation in rural areas and is equivalent to a standard septic system. It ensures enough wastewater treatment capacity, including recycling and conventional treatment, to support the projected return flow connected to treatment. The desalination potentials have been estimated following the approach in (S. Parkinson et al., 2019a), where desalination capacity data are inferred against GDP trends using a logistic function. Here data on water stress from (Byers et al., 2018) have been added to the function to include the climate dimension in the projections (see Figure S 4.1.4).

We use the approach detailed by (Fricko et al., 2016) to calculate water withdrawal and return flows from energy technologies. Each energy technology requiring water is provided with a withdrawal and consumption intensity (e.g., cubic kilometers per GWh), allowing the model to translate technology outputs into water requirements and return flows, which balance with the available supply. For power plant cooling technologies, where the water requirements are calculated as a function of heat rate, the efficiency change in the energy technologies (e.g., lower heat rates) impacts the cooling requirements per unit of electricity produced. The withdrawal and consumption intensities for power plant cooling technologies align with the range reported by (Meldrum et al., 2013a), while additional electricity demands from recirculating and dry cooling technologies are included in the electricity balance computation. Other technologies adhere to the data provided by (Fricko et al., 2016).

Table 3.1: Data sources used for various parameters and input variables

Parameter	Description	Data
Basin boundaries	Basin boundaries used from the Hydro SHEDS database (Lehner et al., 2006) to create new spatial units in the water sector	All the processed files are available in the GitHub repository in CSV format (~data/water/delineation)
Power plant water use	All power plants' water uses and investments (Meldrum et al., 2013b) are updated based on the latest powerplant database from Platts (<i>Platts Market Data – Electric Power S&P Global Commodity Insights</i> , n.d.) Hydropower use and investments (Grubert, 2016) Parasitic electricity requirements (Dai et al., 2016) Regional shares of cooling (Raptis et al., 2016)	All the processed files are available in the GitHub repository in CSV format (~data/water/ppl_cooling_tech)
Water Availability	Runoff & groundwater recharge from the GHM CWatM model (Burek et al., 2019) outputs of the ISIMIP project (Frieler et al., 2017). The outputs are spatially and temporally processed for further use. To parameterize the historical groundwater extraction, we use groundwater abstraction data from (Wada et al., 2014) and historical water withdrawals from (Wada et al., 2016). The fraction of groundwater abstraction to the overall withdrawals determined the 'groundwater fraction'. This value is then used on the actual historical water demands included in the model to set the amount of pumping capacity for the future horizon. For the cost of groundwater pumping, depending on the aquifer depth, we use groundwater aquifers depth data (Fan et al., 2013) and energy consumption values from (Vinca, Parkinson, Byers, et al., 2020b) and (Liu et al., 2016).	All the processed files are available in the GitHub repository in CSV format (~data/water/water_availability)
	Freshwater Energy consumption per unit of water (Liu et al., 2016)	0.01883 (0.0011 - 0.03653) kwh/km3
	Techno-economic values from (Vinca, Parkinson, Byers, et al., 2020b) and (Burek et al., 2018)	Investment costs assumed for the whole world. groundwater infrastructure: 155.57 million USD/km3, surface water extraction: 54.52 million USD/km3
Water demands	Municipal water demands are spatially and temporally processed using the approach followed by (Wada et al., 2016) and using recent and updated data. Irrigation water demands are used from the GLOBIOM model for a set of scenarios aimed to achieve multiple, different SDG goals (Frank et al., 2021a) Treatment & access rates are re-calculated using the approach described in (S. Parkinson et al., 2019a) and using additional dependent variables in the regression analysis. These treatment and access rates are then used with the return flows from (Wada et al., 2016).	All the processed files are available in the GitHub repository in CSV format (~data/water/water_demands)
		GLOBIOM Emulator
Water Infrastructure	Water distribution & wastewater treatment energy footprints are used by (Liu et al., 2016)	All the processed files are available in the GitHub repository in CSV format (~data/water/water_demands)

An upper constraint on desalination potential is implied in the model using multiple regression parameters (GDP, Water Stress Index (Byers et al., 2018), Governance (Andrijevic et al., 2020a), and distance to coast. We use the Desal Data dataset (Global Water Intelligence, 2016) to evaluate the existing (or historical) capacity of desalination units worldwide, gathered at the BCU level.

All the processed files are available in the GitHub repository in CSV format (~data/water/water_infrastructure)

The energy footprints of various components of the water sector, including supply (surface water and groundwater extraction), distribution (urban and rural), and wastewater treatment (treatment, recycling, and re-use), are interconnected with the electricity needs of the energy sector. This connection is established through basin-region mapping, which enables the spatial aggregation of appropriate fractions of electricity requirements to the region (R11) where the water sector's electricity consumption is managed. Table 3.1 indicates different references used for electricity requirements per unit of water infrastructure activity at various stages.

3.3.2 Climate Impacts

The following climatic impacts are covered in the nexus module and this study: Changes in crop yield, variations in precipitation patterns and drought severity, renewable energy potentials, cooling and heating energy demand, desalination potential, and cooling water discharge for energy use. Impacts on biodiversity are partially included in the evaluation whereby natural land serves as a high-level proxy indicator for the level of biodiversity. This method covers land-use change-induced consequences, which are the primary cause of biodiversity loss in the short term but excludes direct climatic impacts. Thus, it primarily reflects the consequences of climate and SDG policies. All impact data is derived from the Intersectoral Model Intercomparison Project (ISIMIP) (Frieler et al., 2017) to maintain internal consistency across all indicators and models. The remainder of this section describes the model-specific representation of biophysical climate impacts across the energy and water land sectors and the methodological steps required to implement or update new climate impacts. We use the data for RCP2.6 and RCP6.0 to consider the climate impacts, i.e., emission pathways reaching 2.6 W/m² and 6.0 W/m² forcing levels in 2100. We have not included GDP and labor productivity implications to focus solely on biophysical impacts.

The climate impacts on hydropower energy supply have been based on (Gernaat et al., 2021). The difference between current and projected spatially explicit climate parameters is translated into spatially explicit energy supply estimates, translated to

regional cost-supply curves. The climate data were used as input to calculate hydropower potential. It includes the theoretical potential and the upper limit of resource availability based on physical and hydrological conditions. The climate impacts were calculated for the historical and future periods using the ISIMIP database. The maps of technical potential, combined with economic information, have been used to generate cost-supply curves. These curves show the cumulative technical potential against the production cost, showing that each location's production cost depends on its productivity. Cost-supply curves are widely used in IAMs to model the long-term cost development of renewable energy technologies. These curves indicate resource depletion, as the most productive sites are slowly being depleted, and thus, higher cost-incurring sites need to be used. On the other hand, note that climate impact on non-hydro renewables is not included in this study because excluding non-hydro renewables in the IAM is not expected to lead to significant discrepancies between the scenario results. (Gernaat et al., 2021) presented relatively small impacts on renewable energy supply.

Table 3.2 Summary of biophysical impacts

Biophysical climate impacts	Approach
Renewable supply (hydro)	Different costs supply curves based on 0.5x0.5 grid calculations (Gernaat et al., 2021)
Heating/cooling demand	Impact via population-weighted heating and cooling demands based on the work of (Byers et al., 2018; Mastrucci et al., 2021) 0.5 x 0.5 grid
Water availability	Runoff and groundwater recharge from CWatM calculated at 0.5 x 0.5 grid (Burek et al., 2020)
Crop yields	Climate impacts on crop productivity, nitrogen, and irrigation from the CMIP6 projections of the crop-model EPIC-IIASA are used in GLOBIOM. EPIC-IIASA estimates the impact of climate on rice, maize, wheat, and soy and feeds into GLOBIOM following (Müller & Robertson, 2014)
Cooling technology capacity factor	Climate impacts on cooling water discharges for cooling technologies of fossil power plants are used from (Yalew et al., 2020b)
Desalination potential	Desalination potential climate impacts are based on water stress outputs from the combinations of GHMs & GCMs from (Byers et al., 2018)

Regional cooling and heating demand days are based on the dataset and study by (Byers et al., 2018), who derived their climate data from an ensemble of downscaled and bias-corrected global climate models (ISIMIP2). The data represents gridded global surface air temperature data at the daily resolution, summarized to decadal timesteps and a monthly mean and subsequently aggregated to countries, weighted by SSP population. In this study, to estimate the corresponding energy demand in socioeconomic, technology, climate, and policy scenarios, we used two modules within the MESSAGEix-Buildings framework: CHILLED (Cooling and Heating gLoBaL Energy Demand model), a bottom-up engineering model to estimate residential space heating and cooling energy demand; and STURM (Stock TURnover Model of global buildings), a stock turnover model based on dynamic material flow analysis (MFA) to assess the future evolution of the building stock (Mastrucci et al., 2021). The resulting estimates of country energy demand for cooling for SSP2 under RCP2.6, RCP6.0, and the assumption of fixed historical temperature (no climate scenario) are aggregated from the country to the MESSAGE region. They are added to the model as a subcategory of the residential demand (Figure S5).

Climate impacts on agriculture and assessment of future hotspots are assessed in GLOBIOM by systematically integrating crop yield information from EPIC (Balkovič et al., 2014) (run for the different GCMs) for 4 crops (corn, wheat, maize, and rice) and applying it using some assumption to our other crops (Jägermeyr et al., 2021). IIASA's Global Forest Model (G4M) models forest growth as a response to climate (Kindermann et al., 2008). The G4M uses a dynamic net primary productivity model to consider how growth rates are affected by changes in temperature, precipitation, radiation, as well as soil properties. G4M works with a monthly step, and the highest spatial resolution is 1 km². The model estimates the impact on net primary productivity, mean annual increment, standing biomass, and harvestable biomass. Factor changes of mean annual increment and biomass accumulation under a certain degree of climate change compared to a no climate change scenario are multiplied by the default rates in GLOBIOM. GLOBIOM's biophysical model incorporates agricultural yield, input requirements, and water availability for irrigation from the CWatM. This integration allows us to evaluate the relative effects of climate change on production, consumption, and market conditions and the autonomous adaptation to the impacts resulting from the GLOBIOM. Irrigation water withdrawals from the GLOBIOM are then linked to the nexus module, which balances the water system across other uncertainties.

3.3.3 SDGs

This section describes the energy, water, and land SDG measures in the model, which align with SDG2 (Zero hunger/food access), SDG6 (Clean water and sanitation/water access), SDG7 (Affordable and clean energy/energy access), SDG15 (Life on land/biodiversity). SDG13 (Climate action) is also implicitly included in the framework when emissions constraints are included in the scenario design. In this study, SDG13 is represented by achieving a 2.6 W/m² (or a well-below 2 degrees) target in 2100. This is essentially the goal of the SDG, limiting climate change following the Paris agreement. Table 3.3 provides an overview of all the (non-climate) nexus SDG measures, their representation in the models, and the indicators to measure progress. The main criteria for including measures have been: 1) They should maximally benefit the overall goal and 2) They should be unambiguous and quantifiable, and 3) They should allow for consistent implementation across models. The interaction between these measures and the other SDG categories is relatively limited.

The MESSAGE-Access-E-USE (end-use services of energy) model (Poblete-Cazenave et al., 2021; Poblete-Cazenave & Pachauri, 2018) is used for the analysis of households' energy access to modern energy services for heating and cooking and has already been used on a global level to study demand in different socioeconomic pathways (Pachauri et al., 2021; Poblete-Cazenave & Pachauri, 2021). An estimation model takes as input micro-level data from nationally representative household surveys covering different regions of the world to estimate behavioral preference parameters that explain the choices of appliances and energy demands for different end uses based on household socioeconomic and demographic characteristics. Then, a simulation module uses the preference parameters estimated in the first module and additional external drivers that present potential pathways of socioeconomic growth and energy prices to simulate future appliance uptake and household energy demand under each scenario. This process is not internalized in MESSAGEix-GLOBIOM, but instead, a first iteration is performed to estimate the share of the population with access to modern energy sources for cooking (as opposed to traditional biomass or kerosene) given a fixed GDP pathway (SSP2) and energy prices related to each policy scenario. The model also assesses the implication of additional SDG policies regarding costs and transformations in the energy demand. This is, however, separated from the solution of MESSAGE because an iterative procedure would alter the GDP pathways in the macroeconomic component of the model (MACRO).

The SDG6 narrative is incorporated by applying supply and demand-side development across the water system. The supply-side measure includes constraints on available surface water as environmental flows. The rivers' environmental flows help protect river-related ecosystems from achieving SDG target 6.6 (protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers, and lakes). We use the Variable Monthly Flow (VFM) method (Pastor et al., 2014a) to constrain the monthly surface water available for human use based on environmental flow requirements (EFRs) for wet and dry seasons. (Pastor et al., 2014). This method implies that water withdrawals cannot exceed the available residual supply after considering the EFRs. Some regions may be unable to adapt environmental flow targets in 2030 based on historical trajectories due to high withdrawals or fewer governance capabilities. We categorized these basins based on the development status of countries specified by the World Bank and implemented a lower environmental flow target in the respective regions from 2030 onwards and increased the target till 2050, thus following the trajectory of basins with high adaptive capacity. These environmental flow targets also vary across climate impact scenarios. It enables assessing the response to mitigating future demand growth. The demand-side measures for SDG6 in the water system include targets for reaching sustainable water consumption across all sectors. We constrain the capacity of the water infrastructure system for integrating water access and quality targets. The connection and treatment rates are endogenized in the withdrawals and wastewater collection. These rates are changed to allow shifts in water withdrawals for universal piped access. Wastewater treatment capacity is increased to treat half of all the wastewater collection in the infrastructure system. The connection and treatment rates are adjusted for the basins that can readily adapt; the targets for 2030 are assigned to the basins with more adaptive capacity than those with less adaptive capacity. Increasing the fraction of wastewater treatment also helps to protect ecosystems related to water, thus contributing to achieving SDG6 target 6.6. The rates are projected in the baseline (non-SDG) scenario using a logistic model by combining income projections fitting to national historical data using the approach described in (S. Parkinson et al., 2019a).

Table 3.3: SDG measures and indicators. Where possible and relevant, measures are fully implemented in 2030 and maintained until 2100 (see this [link](#) for SDG description)

SDG	Measure	Indicators
SDG 2 FOOD	- < 1% undernourishment goal by 2030	- Food production
	- Decrease animal calorie intake to 430 kcal/capita/day by 2030 from current levels in overconsuming countries (USDA recommendations for healthy diets)	- Food prices - Population at risk of hunger
	- 50% reduction in food waste compared to SSP2 assumptions	- Food production - Food prices - Population at risk of hunger
SDG6 Water	- Limited irrigation water withdrawals to sustainable removal rates that do not jeopardize ecosystem services and environmental flows (Frank et al., 2021a)	- Water withdrawal (irrigation)
	- Based on the variable monthly flow (VMF) method developed by (Pastor et al., 2014a) where 60% and 30% of the mean monthly natural flow are reserved for ecosystems in low and high flow periods, respectively.	- Water and environmental flows
	- A minimum of half of all return flows will be treated by 2030 for developed regions and 2040 for developing regions.	- Population with access to clean drinking water
SDG7 Energy	- Results from the MESSAGEix-GLOBIOM are iterated through the MESSAGE-Access-E-USE (end-use services of energy) model by the provision of access targets based on income levels and GDP pathways and population with access to modern energy access and the energy demand adjustments are calculated.	- Energy prices - Population with access to modern energy services
	- 90 % access target to modern cooking energy for cooking by 2030	- Energy prices -Population cooking with traditional biomass
SDG15: Life on land	- Based on (Frank et al., 2021a) expansion of protected lands to 34% in 2030 was assumed, and highly biodiverse areas were identified based on the UNEP- WCMC Carbon and Biodiversity Report (Kapos Ravilious C. et al., 2008) their conversion to agriculture or forest management from 2030 onwards was prohibited.	- Natural land area

The irrigation conservation approach is implemented to reduce the irrigation withdrawals and reallocate water to other sectors, thus contributing to target 6.4 (Frank et al., 2021a). (Pastor et al., 2019b) mentions how the reduced water approach in the irrigation sector in the GLOBIOM model accounts for environmental flows, and the water is re-allocated to the environment and domestic uses by saving from the irrigation sector. The model chooses the irrigation water withdrawals based on the land-use emissions and associated costs to keep the land-related trade-offs with water and energy intact through the GLOBIOM emulator. The model enhancements do not cover all SDG6 targets, such as flood management and transboundary cooperation across basins. Concerning biodiversity protection, the GLOBIOM model assumes increased efforts and a doubling of the AICHI Biodiversity target 11 (e.g., increase the total surface of protected areas to 17% by 2030 (Bacon et al., 2019). In addition, we use the UNEP-WCMC Carbon and Biodiversity Report (Kapos Ravilious C. et al., 2008) to identify

highly biodiverse areas and prevent their conversion to agriculture or forest management from 2030 onwards. We consider the area highly biodiverse where three or more biodiversity priority schemes overlap (Conservation International's Hotspots, WWF Global 200 terrestrial and freshwater ecoregions, Birdlife International Endemic Bird Areas, WWF/IUCN Centre of Plant Diversity and Amphibian Diversity Areas). We estimate residential cooling gaps as the extent of the population needing space cooling without access to it and the additional energy demand required to close this gap and provide essential cooling comfort to all (Mastrucci et al., 2019). Minimum cooling requirements are calculated under the assumption of durable housing construction and conservative per-capita floor space and cooling operation to provide decent living standards (Kikstra et al., 2021), assuming the gap is covered with current cooling technologies, including fans and AC.

3.3.4 Flexibility across scales

As mentioned in section 2, the module is flexible to adapt to a different spatial dimension with a higher resolution. In this case, we evaluated downscaling the global module for a particular country Zambia. The energy sector is downscaled using the country model generator, which is used for various country-scale energy sector analyses, e.g., (Orthofer et al., 2019). However, the nexus module also allows the water system to be prototyped rapidly for a country/basin level. The water reference system described in previous sections is pre-processed onto the higher-resolution spatial units from the gridded datasets, and a base scenario is produced. The workflow diagram to produce the country scale model is shown in supplementary Figure S6. The Zambian scale module is being used to develop an integrated platform combining different high-resolution sectoral models (Water Crop Evapotranspiration model to estimate crop water demand for different crops (Tuninetti et al., 2015), an electricity demand assessment platform, M-LED for communities without electricity supply (Falchetta et al., 2021), OnSSET tool to assess least-cost electrification technologies and investment requirements based on electricity demand and energy potentials (Korkovelos et al., 2019). (Falchetta et al., 2022b) discusses the application of such linkages and further details.

3.4 Results & Discussion

The MESSAGEix-GLOBIOM nexus module generates outputs that allow for an understanding of the relationships between water, energy, and land at both the basin

and global levels. These outputs include information on water availability in different regions, key indicators related to the Sustainable Development Goals, and sector-specific climate impacts and it spans multiple sectors to inform about integrated pathways. Figure 3 presents a summary of configurations of sectoral outputs possible from the current module. One key feature is its ability to produce scenario combinations, which help to reveal the sensitivities and assumptions underlying different pathways. By analyzing the energy, water, and land implications of these scenarios, it is possible to identify robust pathways resilient to changing conditions and meet the needs of various stakeholders. Overall, the outputs generated by the module provide valuable insights into these resources' interdependent nature and can inform regional decision-making. As mentioned in the previous section, any scenario combinations are possible from the module. However, to evaluate the model's applicability across climate and SDG scenarios in combination, we formulated six scenarios that alternate different assumptions. We used a combination of SSP2 pathways combined with RCP2.6 & RCP6.0 for the current setup. The upcoming work will include more SSP dimensions in combination with RCPs to have more consistent assumptions across scenarios.

The scenario formulation we used to describe the results is mentioned below.

- **Reference** scenario includes historical climate assumptions. The data used in this scenario doesn't include any climate effects for the future.
- **Impacts** scenario includes climate impacts across the EWL sectors. This scenario assumes RCP6.0 scenario for different biophysical climate impact indicators, as indicated in section 3.2.
- **Impacts_LU** scenario assumes only land use impacts from GLOBIOM.
- **Impacts_WAT** scenario assumes only water sector impacts on the renewable water availability and capacity factors of cooling technologies for thermal power plants.
- **Impacts_EN** scenario assumes the energy sector impacts, including the hydropower impacts and cooling/heating energy demands.
- **SDGs** include all SDG-related assumptions indicated in section 3.4

Energy	Water	Land	Socio-economics
<ul style="list-style-type: none"> • Energy use (Primary, Secondary, Final) • Energy prices • CO₂ emissions pathways • Capacity requirements • Energy supply portfolio • A/C cooling gap • Investment pathways • Energy use of water commodities) • Adjusted residential demands with increased access to electricity 	<ul style="list-style-type: none"> • Water withdrawals based on constraints • Water supply outlook (combination of different sources) • Capacity requirements of water infrastructure technologies (wastewater, water distribution) • Investment in the water infrastructure sector • Drinking & irrigation water marginal prices • Water footprint of energy sector 	<ul style="list-style-type: none"> • Water Withdrawals for Irrigation • Crop Yields • Land Cover (different categories) • Agriculture production & demand • Fertilizer use & intensity • Land use CO₂ emissions 	<ul style="list-style-type: none"> • Population with access to drinking water, sanitation • Urban & rural municipal demands • Population with access to electricity, clean-cooking fuels • Population with risk of hunger

Figure 3.3 Summary of output indicators that are possible from the MESSAGEix-GLOBIOM nexus module. These outputs are long term pathways and much of these outputs can be further disaggregated onto the technology level.

To understand the biophysical effects of climate change on multiple sectors, we compared the scenarios, including climate impacts (Impacts, Impacts-EN (energy sector impacts), Impact-WAT (water sector impacts), Impacts-LU (Land use impacts), and SDGs to see how some of the key EWL indicators respond to combined and individual sectoral impacts and SDGs with a Reference scenario that includes historical climate assumptions (scenario without any climate impacts or SDGs). Despite being physically impractical, the Reference scenario aids in comprehending the results of biophysical consequences by projecting historical climate data into the future. The model incorporates the biophysical consequences, highlighting potential outcomes in various sectors.

Our study allows the monitoring of water balance flows at varying stages, offering an in-depth understanding of global water management and the intricate nexus between water, energy, and land. These interactions are depicted in Supplementary Figure S 4.1.4 (Sankey diagram), along with input details and assumptions expounded in Section 3.1. The module provides a nuanced perspective, capturing the complexities of water resources and their utilization at both global and basin scales. To compare the water flows from the literature, we compared global water resources (total runoff) to be in the range of approximately 47219.79 km³/yr., a figure that aligns with those reported by (Burek et al., 2020) and (Sutanudjaja et al., 2018). Water withdrawals or water extractions, as interpreted from our model's outputs across various scenarios, fell within the 3365–3656 km³/yr., echoing figures found in established literature (refer to Table 3.4 for a comparison). Global wastewater collection, an essential constituent of water management, was quantified as an exogenous input in our model at approximately 310.22 km³/yr. in 2020. This figure finds resonance with the estimates reported by

(Jones et al., 2021), albeit with slight discrepancies due to differences in underlying assumptions and calculation methodologies. Wastewater treatment ranges from 155.7 to 171.9 km³/yr., closely aligned with the 186.6 km³/yr reported by (Jones et al., 2021). The study also scrutinized agricultural withdrawals, an important sector of water use. For 2020, our model computed this at 2666.36 km³/yr., a figure between 1250–2000 km³/yr reported by (Burek et al., 2020) and closely matching the 2735 km³/yr. posited by (Sutanudjaja et al., 2018). Figure 3.4 shows a range of water supply portfolios with varying water demands. Even though renewable energy sources are crucial overall, these portfolios' makeup shows significant regional variation when looking at the regional results. Regional variations in these water balance flow and critical indicators for the energy, water, and land (EWL) sectors are depicted in supplementary sections S3 and S4. The choice of supply sources within each basin depends on the availability of resources and associated operational and investment costs. Characterizing supply portfolios across various river basins will be the focus of future research projects under varying scenarios and water supply reliability levels. However, this structure allows us to see the water management portfolios linked with the energy and land sectors under varying climate and sustainable development scenarios.

It is worth noting that while these comparisons pertain to the year 2020, a key novelty of our study is its ability to depict prospective pathways in an integrated manner. The study accounts for socioeconomic assumptions, climate impacts, and sustainable development goals. Moreover, our model provides critical estimates of the investments and capacity requirements at each five-year timestep, delivering comprehensive insights into future water management needs. Furthermore, these indicators have been juxtaposed with existing literature in Table 4, thereby reinforcing the robustness of our study. This research provides a holistic and dynamic perspective on the nexus of global water, energy, and land management. It is poised to inform and influence policymaking and investment decisions, guiding us toward sustainable future utilization of these vital resources. To capture the dynamic responses of the climate system, the model's response to climate impacts employs a multifaceted strategy that includes both endogenized and exogenous outputs. The use of the EPIC, which provides information on irrigation responses and their subsequent effects on crop yields, is one prominent example. Then, these yield outputs are incorporated into the GLOBIOM, where adaptation responses are endogenized, causing a reallocation of land use system resources based on climate impacts. Notably, this reallocation includes decisions

regarding land use that directly affect water use in irrigation. The irrigation withdrawal computations are then used by the MESSAGEix GLOBIOM, which effectively balances water supplies by considering irrigation withdrawals in conjunction with withdrawals from other sectors under changing climate conditions. In contrast, responses in the water sector are contingent on the availability of resources under various climate scenarios. The effects of climate change on hydrology directly impact the availability of resources, compelling the model to adapt and consider alternative supply sources.

Similarly, the energy sector incorporates endogenized decisions based on the effects of climate-induced changes in the capacity factor of thermal power plants. These changes have implications for thermal power generation and the feasibility of hydropower installations in various regions. Additionally, the demand for cooling is acknowledged as a significant factor influencing energy demands. Through this integrated approach, the model systematically accounts for and responds to the biophysical impacts induced by a changing climate, providing a comprehensive assessment of the interdependence and implications across multiple sectors.

Sectoral withdrawals primarily drive water extraction by source, with irrigation withdrawals from the GLOBIOM model making up a sizable portion. Supplementary Figure S4.1.3 depicts the outlook for water extraction under the reference scenario. The effects of climate on crop yields vary, with sugar crops experiencing a more significant impact (16%) than cereals (~1%). The net yield effect is affected by fertilization intensity, with increased water use efficiency influencing irrigation water needs. However, these results require cautious interpretation because our study did not account for cultivar optimization. The results affect water withdrawals and consequently influence the portfolio of water supplies. It is essential to highlight the role of enhanced irrigation efficiency assumptions in the SDGs, which result in a 29% average reduction in total water withdrawals compared to climate impacts concurrent to the study by (Frank et al., 2021a). In addition, these effects contribute to a 28% decrease in the marginal price of potable water due to adaptive responses to climate change. In contrast, pursuing the SDGs can result in a significant price increase due to increased allocation to environmental flows. Figure 3.5 summarizes key indicators across the scenarios.

The results demonstrate that renewable surface water and groundwater are limited and vacillate across different climate scenarios. These effects decrease

renewable water consumption, which is more evident in the land than in the water sector. In addition, our model indicates an increase in the use of alternative water sources such as brackish water, effluent, and desalination in certain regions, indicating that renewable water resources are limited in these areas. These observations serve to highlight the significance of the SDGs further. For instance, when aligned with SDG 6 targets, the model predicts a 24% reduction in water consumption, resulting in a more sustainable water allocation to environmental flows.

The geophysical characteristics and land use effects of various locations significantly impact the global effects of climate change on the water sector. Some areas may obtain benefits, while others may suffer negative consequences. In addition, the study found that the adaptive response to climate impacts reduces by an average of 11% the number of individuals exposed to hunger. Compared to the SDGs (30%), where specific assumptions were made to reduce the danger of hunger, this reduction is less significant (Figure 3.5).

The implications of climate change are interrelated and can have cascading effects on various sectors; thus, it is crucial to stress that these results should be viewed in the context of the complete model. Overall, the findings indicate the need for more research to fully comprehend the potential effects of climate change on diverse sectors and the possibility that incorporating biophysical consequences can substantially impact the outcomes of climatic scenarios. As a result of the effects of climate change, this shows that certain regions are transitioning to more sustainable energy sources. Overall, the study's findings illustrate the significant implications of climate impacts in mitigation scenarios on the energy mix and the possible co-benefits of adaptation while mitigating climate change. It is important to note that these results are based on a specific model and situation and should be interpreted as a general trend. Future research and forthcoming publications will expand on these findings and give policy-relevant insights into the areas. This configuration can benefit policymakers, energy corporations, and other stakeholders in comprehending the effects of climate change on the electrical generating mix and developing adaptation measures.

Table 3.4 Comparison of EWL indicator results for the year 2020 with published literature sources for model validation.

Variable/Indicator	Model Value 2020	Comparison with other studies
Primary Energy (EJ)	595-599	613 (GCAM5.3_NAVIGATE); 591.06 (IMAGE 3.2); 569.36 (REMIND-MAgPIE 2.1-4.2) ;575.29 (MESSAGEix-GLOBIOM_1.1) (Harmsen et al., 2021)
Energy Supply Investments (billion USD/yr.)	1325-1401	1148.13 (IMAGE3.2); 1036/41 (MESSAGEix-GLOBIOM_1.1); 1208. 66 (REMIND-MAgPIE 2.1-4.2) (Harmsen et al., 2021)
Agricultural Production	3350.53	4400.6 (IMAGE3.2); 4044.95 (MESSAGEix-GLOBIOM_1.1); 15189.47 (REMIND-MAgPIE 2.1-4.2) (Harmsen et al., 2021)
Cereal Yield (t DM/ha/yr.)	3.71	3.68 (IMAGE3.2); 3.76 (MESSAGEix-GLOBIOM_1.1); 3.53 (REMIND-MAgPIE 2.1-4.2) (Harmsen et al., 2021)
Yield Sugarcane (t DM/ha/yr.)	18.67	8.64 (IMAGE3.2); 19.75 (MESSAGEix-GLOBIOM_1.1); 30.58 (REMIND-MAgPIE 27.09) (Harmsen et al., 2021)
Water Withdrawals (km3/yr.)	3656-33659	2200 – 4200 (Burek et al., 2020) , 3912 (Sutanudjaja et al., 2018)
Water Resource (km3/yr.)	47219.79	51800±1800 (Burek et al., 2020); 42393 (Sutanudjaja et al., 2018) ; 42000 – 66000 (Haddeland et al., 2014)
Groundwater Recharge (km3/yr.)	15000	19000 920 (Burek et al., 2020); 27756; 12666 – 29 900 (Mohan et al. 2018)
Agriculture Withdrawal (km3/yr.)	2666.36	2000 [1250-2400] (Burek et al., 2020) ;2735 (Sutanudjaja et al., 2018)
Wastewater Collection (km3/yr.)	310.22	224.4–226.9 (Jones et al., 2021) 380 (Qadir et al., 2020)
Wastewater Treatment (km3/yr.)	155.7- 179	186.6– 189 (Jones et al., 2021)

The coupling of the SDGs with climate policies and implications can give valuable insights into how to solve climate adaptation problems and is part of the upcoming publications. While there have been numerous publications on integrating SDG dimensions into Integrated Assessment Models (IAMs) such as (Baumstark et al., 2021; Soergel, Kriegler, Weindl, et al., 2021; van Soest et al., 2019; D. P. van Vuuren et al., 2022), this study stands out due to its novel approach of combining SDG policies with climate goals and impacts and evaluating their effectiveness in understanding the climate adaptation narrative. The findings emphasize the need to examine the regional heterogeneity of development objectives to comprehend how various areas might adapt to climate change impacts while concurrently reaching development goals. Overall, the SDG-related outputs of the module may be utilized to broaden and improve our understanding of global and regional human development indices. The geographically variable insights gained from this study can aid in advancing our understanding of how various places might adjust to the effects of climate change while pursuing development objectives. We chose metrics and studied the percentage difference between scenarios that assumed the SDGs and those that did not (Figure 3.5). Although many IAMs scenarios already include the SDG dimensions, the innovation in this module combines

SDG scenarios with climate impact scenarios. This scenario will be used in the upcoming studies to assess the benefits of mitigation and adaptation while ensuring sustainable development targets.

It is important to emphasize that the results related to the various scenarios described in this study should be interpreted carefully. They depend on several assumptions and should be viewed in the context of the focal region and time frame, even though they offer valuable insights into the potential economic implications of specific water management strategies. Due to variations in assumptions, data inputs, and other factors, various modelling methodologies may produce various conclusions. It is feasible to develop a more thorough understanding of the potential effects of various water management systems and to pinpoint the most successful and efficient methods by contrasting the outcomes of different models.

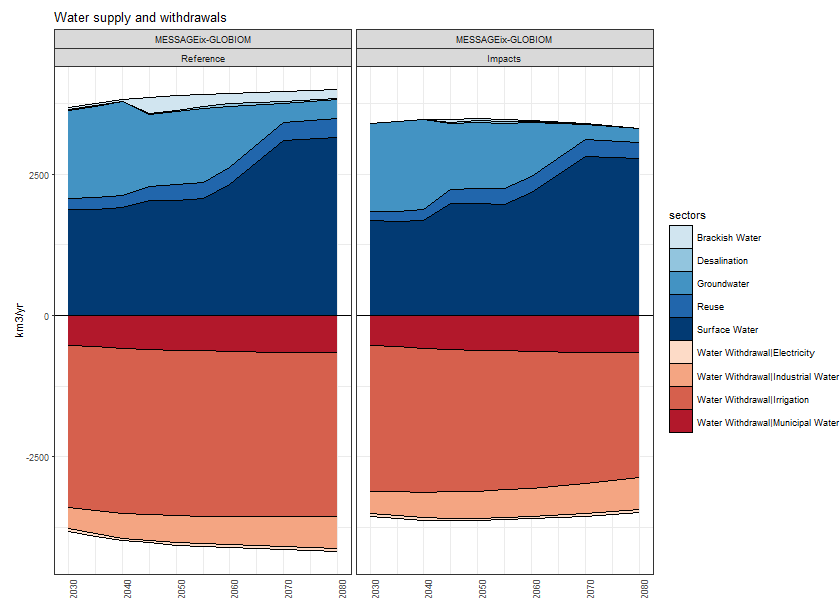


Figure 3.4 illustrates the supply and withdrawal components of the global water balance are reported from the model outputs for the Reference and Impacts scenarios. A range of blue hues are used to represent the supply sources, and a range of red hues are used to represent the withdrawals. Water supply and withdrawals are determined by evaluating the resources that are available across temporal (5-year time step) and spatial units (B210) as well as techno-economic parameters such as capacity installations, investments, and variable costs. The interplay between supply and withdrawals within the scenarios taken into consideration is highlighted in this figure, which offers insightful information into the complex dynamics of water management.

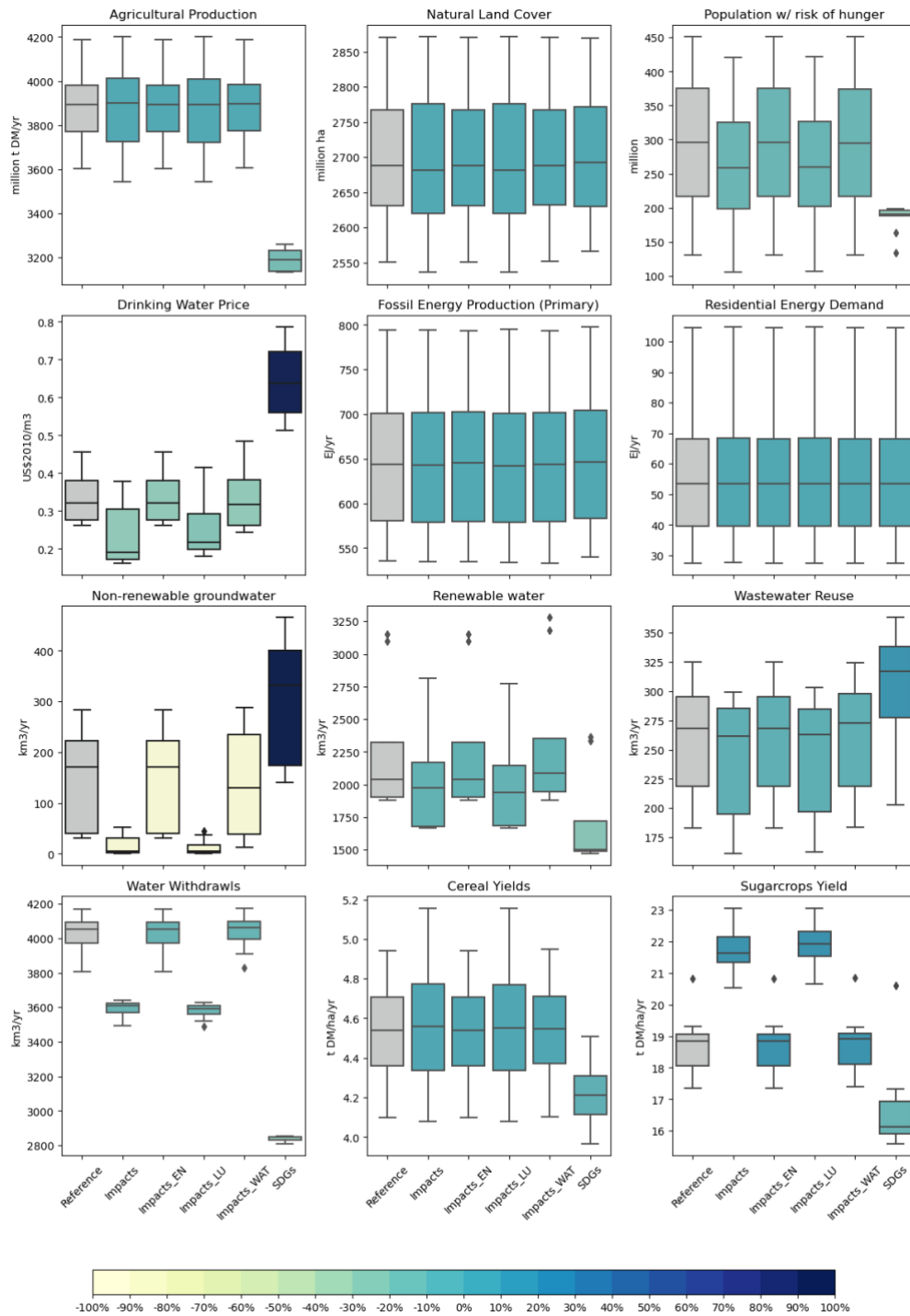


Figure 3.5 A Comparison of Key EWL Indicators across Multiple Scenarios It shows the boxplot distributions for selected indicators from the model output. From 2030 to 2080, these are displayed against five distinct scenarios: reference, impacts, impacts_LU, impacts_EN, impacts_WAT, and SDGs. The reference scenario, which stands out visually by having a gray hue, serves as a benchmark for other scenarios. The variance in color between the remaining boxplots represents the percentage change from the reference scenario. The most important aspect of this graph is the relative consistency of energy-related metrics across scenarios, in contrast to the extreme variability of nonrenewable water usage, which indicates that these energy indicators show a lesser difference under scenarios than water or land indicators.

3.4.1 Further development

While the model includes detailed implementation of the water sector and representation of biophysical climate impacts, we identify areas where our model lacks certain aspects and uncertainties. Since we look at the integrated systems, we do not include inter-basin or spatial unit transfers, which can be crucial for answering transboundary challenges in the river basins. Moreover, we currently do not account for water storage, a potentially important aspect of water resource management where we can see the water storage during a high flow season and its use during a low flow season. We use the flow percentiles approach to partially address this concern.

In terms of ensuring consistency, the reliance of the Nexus module on a multitude of data sources to depict climate impacts can present challenges. In addition, the sensitivity of indicators to these impacts and the uncertainty of the Global Hydrological Model (GHM) is more significant than those of climate models. The model's representation of alternative water constraints, such as the economic consequences of fossil groundwater extraction to reduce water consumption, will be explored in future research by focusing on more realistic groundwater assumptions. In addition, the current structure of the model assumes an endogenous adaptation response when impacts are included, which may not fully capture the complex dynamics of the Energy-Water-Land (EWL) sectors.

Future research will endeavor to address these limitations. We intend to investigate a broader range of climate impact dimensions, including a higher tolerance for statistical climate extremes at a sub-annual temporal resolution. Future iterations of the model will incorporate the most recent data on climate impacts, and we will seek to identify more reliable and consistent data streams across all sectors.

In addition, we aim to distinguish the roles of impacts and adaptation responses within the EWL sectors, which will allow for a better understanding of the role of climate and the responses triggered by these impacts in the models. This future work will contribute to the model's refinement and expansion, resulting in a more comprehensive and accurate representation of the intricate interplay between climate impacts, water policy, and reliability.

3.5 Conclusion

This study addresses the research gap of improved EWL nexus, including biophysical climate impact representation within IAMs, by developing a nexus module

for the global MESSAGEix-GLOBIOM integrated assessment model. It enhances the MESSAGEix framework to study the responses to biophysical climate impacts and water constraints across different scales. Representation of interactions with the water sector has been enhanced by implementing endogenous water sector spatial resolution and water constraints by balancing supply and demand at basin scales globally. It can address nexus synergies and trade-offs across EWL sectors on a global scale showing regional results.

To have a holistic outlook of the results, we investigate the sensitivity of various scenarios concerning water and climate. The water sector results are based on water flow reliability to evaluate the amount of available renewable water that is dependable throughout the year. Based on the findings, increasing reliability from low to medium to high results in increased investment in alternate water sources such as desalination, fossil groundwater, and infrastructure, which incurs additional costs. Moreover, the study shows that regional differences influence the cost of alternate water sources and infrastructure. Furthermore, the research on climate impacts highlights the biophysical consequences of climate change on various sectors and the necessity for additional research to comprehend their prospective outcomes. The study also investigates the effects of climate change on the power generation mix, highlighting the transition from fossil to renewable technologies. The results suggest that integrating biophysical repercussions can impact the outcomes of climatic scenarios, and these findings should be regarded in the context of the entire model.

The model is improved to implement river ecosystem constraints, increasing socioeconomic demands, and ecological uncertainties. The module is developed consistent with state-of-the-art software development practices. The whole framework is transparent and flexible to be downscaled to any basin or country worldwide. A first-order model can be rapidly prototyped and further used to answer cutting-edge policy questions on the impacts and adaptation potentials across different basins, utilizing a set of socioeconomic and climate ensemble scenarios. The research will result in addressing the EWL nexus dynamics and interactions in terms of costs, and structural changes concerning future resilient pathways

Data Availability

The code, processed data, and documentation are available at <https://doi.org/10.5281/zenodo.7687578>

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Chapter 4 Envisioning Water Supply System for a Climate Resilient Development Future³

Preamble. The crucial role of water systems is significantly underrepresented in global climate assessments. Using scenarios from two Integrated Assessment Models (IAMs), this study integrates Sustainable Development Goals and Climate Targets to formulate Climate Resilient Development Pathways (CDRP). These pathways integrate responses to climate impacts and sustainable development objectives seamlessly. Our analysis reveals global synergies within the CDRP, as evidenced by reduced water withdrawals, decreased reliance on fossil fuels, and marked socio-economic enhancements — most notably, a decline in populations under water stress and an increase in access to electricity, clean drinking water and clean cooking fuels. We summarize the portfolio of water supply systems across basins and highlight variations in resilience and water supply reliability. As we advocate for these sustainable transitions, it is crucial to assess the adaptive capacity of each basin to ensure that the envisioned pathways are aspirational and attainable.

³ This chapter is planned to be submitted to *Nature Water*

4.1 Context

Rapid climate mitigation and sustainable development are inextricably linked, necessitating policies integrating both aspects. Targeted Policy interventions focusing on healthy nutrition, sustainable consumption, inequality, air quality, and international collaboration are essential to balance these dynamics and highlight the critical role of mitigation in sustainable development (Bertram et al., 2018; Soergel, Kriegler, Bodirsky, et al., 2021). Simultaneously, the adaptation process, which entails adjusting to climate change and its effects, is essential but is frequently neglected in the integrated global assessments (van Maanen et al., 2023).

Integrated adaptation approaches to the water-energy-food (WEF) nexus that aim to build resilience in these sectors can result in increased resource efficiency and coherent strategies for managing the complex interactions and trade-offs among the water, energy, and food SDGs (Mpandeli et al., 2018b; Schipper et al., 2022). Multisectoral Integrated Assessment Models (IAMs) can avoid isolated decision-making, effectively capture these complexities across multiple sectors, and identify the trade-offs and synergies between adaptation and mitigation strategies (van Maanen et al., 2023).

The water system remains fundamental in the system transitions for climate adaptation and mitigation, and it necessitates a more nuanced comprehension of its intersection with the energy and land sectors. Depending on the governing incentives, policies, and governance, many adaptation and mitigation measures can result in either synergistic or maladaptive effects on water use. It is crucial to manage the substantial water footprint of numerous mitigation measures in a socially and politically acceptable manner, to reduce water intensity and enhance alignment with sustainable development (IPCC, 2023). Climate policy assessments have typically focused on energy and land, leaving unrepresented water, a crucial component for achieving local and global climate objectives (Miralles-Wilhelm, 2021). This fragmented focus may impede a comprehensive understanding of climate change impacts and the efficacy of mitigation measures within the constraints of water systems (Douville et al., 2022).

Recent advancements in IAMs provide the potential for a deeper understanding of water system boundaries under climate policies, but the potential is underutilized. (S. Parkinson et al., 2019b) assessed water infrastructure costs for climate mitigation and sustainable development targets but lacks representation of hydrological boundaries and biophysical climate impacts. (Kahil et al., 2018) proposed a continental

scale hydro-economic model but lacked energy and land policy consideration. Recent studies such as (De Vos et al., 2021) and (Doelman et al., 2022) investigated trade-offs and synergies at various scales, offer invaluable insights into the system's intricate dynamics and have the potential to explore the adaptation dimensions of the water system. These results highlight the need for a concerted effort to integrate water management into the broader climate policy framework, recognizing its essential role in adaptation and mitigation and utilizing emergent tools and models to achieve a sustainable future. To better understand the role of water systems under the mitigation, adaptation and sustainable development targets, we present results from two integrated assessment models, MESSAGEix-GLOBIOM and IMAGE.

4.2 Towards Climate Resilient Development Pathways

Recent studies have highlighted the need to incorporate biophysical climate impacts from the Climate Impact Models (CIMs) into IAMs to understand better the risks and damages associated with climate change (Köberle et al., 2021; Piontek et al., 2021a; Rising et al., 2022; van Maanen et al., 2023). Although the representation of impacts in IAMs will not address the local adaptation needs, it allows exploring the opportunity of trade-offs between adaptation and mitigation, such as water-intensive mitigation efforts in water-scarce locations in dynamic and intersectoral ways. Moreover, pathways leading to low warming are increasingly recognized for synergistic characteristics with sustainable development. Simultaneously, sustainable development itself advances, fostering resilience and adaptive capacity. The synergistic benefits of achieving the Sustainable Development Goals (SDGs) in reducing vulnerability and raising living standards influence the design and selection of our scenarios. By analyzing climate mitigation and SDG scenarios, we can determine the proportion of Mitigation and SDG-related expenditures within the water supply system until the end of the century. The recent IPCC report also underscores the imperative to integrate climate impacts within these pathways, highlighting the intricate interplay between climate mitigation, adaptation, and the pursuit of broader societal goals. This complex relationship sets the stage for a profound examination of how climate policy and sustainable development can converge to shape a resilient future (Schipper et al., 2022).

We develop an integrated scenario design within the two IAMs that incorporates biophysical climate impacts from the Inter-Sectoral Model Comparison Project (ISIMIP) (Frieler et al., 2017) for water supply, renewable energy, crop yields, and cooling gaps across the Representative Concentration Pathway (RCP) 6.0 and 2.6 W/m² to examine adaptation responses to these impacts, climate change mitigation targets to maintain global warming below 2 oC, and the Sustainable Development Goals (SDGs) (See Methods for detailed scenario assumptions). The Resilient development pathways defined by IPCC are undefined; however, this analysis attempts to consider a holistic picture of SDG elements pertinent to the energy, water, and land (EWL) sectors, thereby providing a more sustainable development perspective in the context of mitigation and adaptation and giving insights to a Climate Resilient Development Pathway (CRDP). The motivation to examine mitigation strategies alongside the objectives of Sustainable Development Goal (SDG) targets arises from recognizing that relying solely on transformative adaptation is inadequate. Increasing the allocation of resources towards mitigation initiatives can improve the capacity to adapt, leading to a more effective alignment of climate response plans and ultimately reducing the financial burdens associated with adaptation. Our findings suggest that prioritizing SDG investments with mitigation efforts is more advantageous for the water sector than pursuing SDGs without a concurrent mitigation strategy.

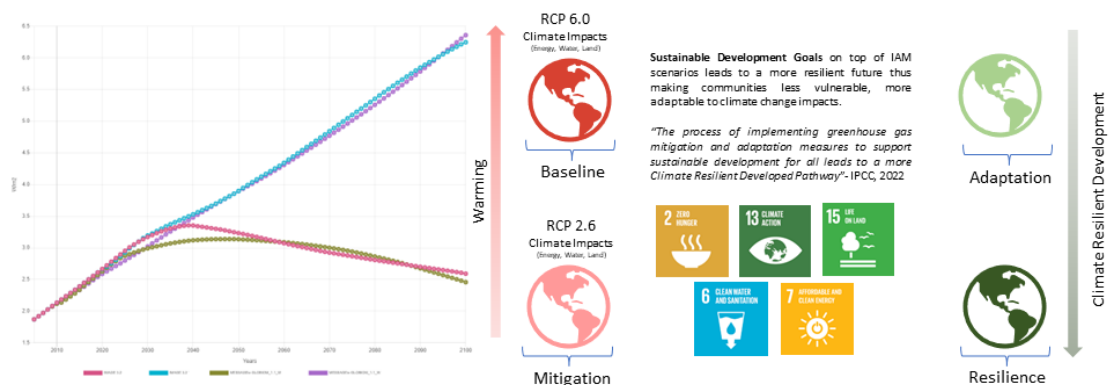


Figure 4.4 Illustration of how the Resilience & Adaptation scenario is designed on top of usual scenarios. The Baseline & Mitigation scenarios also consider climate impacts on renewable energy, water supply, crop yields which allows the scenarios to adjust to these impacts. Adaptation & Resilience scenarios consider the SDG 2,6,7 & 13 assumptions on Baseline & Mitigation scenarios thus allowing to see additional adaptation and resilience dimension in the scenarios.

4.3 Integrated Systems' Synergies & Trade-offs:

This section summarizes the broader pathways by comparing some key WEF indicators across scenarios to set the basis for a more comprehensive understanding

of the water sector's transformation. The analysis establishes the groundwork for targeted interventions within the energy, water, and land nexus interactions required to achieve CRDPs globally. Our findings contribute to the global discourse on sustainability by providing empirically grounded insights that resonate with the imperative to align human progress with stewardship of the environment.

To understand the complex trade-offs and synergies associated with the global energy, water, and land (EWL) sectors under different scenarios, it is essential to identify critical indicators to set the basis for the detailed results. These indicators provide a summary that allows for a comparative evaluation of the impacts and requirements of the Baseline, Adaptation, and Resilience scenarios. We mention the average (2020–2100) energy and water supply investment results reported from MESSAGEix-GLOBIOM as a percentage of GDP to summarize the investments required in each pathway.

Under the Baseline scenario, the necessary investment represents 0.8% of global GDP. In the Adaptation scenario, the required investment increases marginally by 0.89 %. However, the Resilience scenario necessitates a more significant increase in investment, amounting to 1.08 % of global GDP. Regionally, the Middle East, Africa, Asia, and the Former Soviet Union must invest the most per capita in resilience, with respective values of 1.75, 0.9%, and 2.15 % of GDP.

Compared to the Resilience scenario, the Adaptation scenario's investments appear less significant. However, these numbers are model outputs and likely underestimate the costs associated with climate-related damages in a world without mitigation. Although highly pertinent, this topic is outside the scope of our current discussion.

Despite what appears to be a higher investment requirement in the Resilience scenario (1.1% of global GDP), this investment could potentially prevent future losses and additional costs related to climate-related responses. Therefore, the funds allocated to resilience measures can be considered a strategic and economically sound strategy for mitigating future financial risks related to climate change, water, and energy supply challenges.

It is crucial to note that although our study details increased mitigation costs in the Resilience scenario, the real-world socio-economic impacts of climate change in a Baseline scenario, which the world fails to mitigate, could significantly exceed these costs. This investment-focused overview provides an introduction to the

complexities of the examined scenarios and highlights the potential economic consequences of insufficient climate change action. This lays the groundwork for a comprehensive analysis of the trade-offs and synergies inherent to each scenario. Regarding water withdrawal, the Resilience scenario predicts a 30–35 % global decrease by mid-century. This decrease is predominantly due to improved crop yields and irrigation efficiency. Notably, the average global yield has increased by 2%, with specific commodities experiencing more significant increases: sugarcane by 5%, cereals by 4%, and oil crops by 4%.

In the context of water withdrawal, the Resilience scenario implies a global decline of approximately 30 to 35 % by the middle of the 21st century. This reduction can be primarily attributed to improvements in crop yields and the efficiency of irrigation methods. Significantly, there has been a notable gain of 2% in the average global yield, with specific crops indicating more substantial growth rates: sugar crops by 5%, cereals by 4%, and oil crops by 4%.

Asia, being a hotspot for climate change and having the highest population ratio and the highest amount of global water withdrawals, demonstrates a comparatively lower level of reduction in the Resilience scenario when compared to other regions, such as OECD 90 countries. This may be attributed to the increasing pressures caused by population stress. However, in the Resilience scenario, a greater abundance of surface water is available globally. It is essential to acknowledge variations in the features of different basins. Regionally, the hydrological models in the RCP6.0 scenario demonstrate a rise in water availability as compared to RCP2.6 and vice versa. In general, the regions of Asia, the Middle East, and the Former Soviet Union are exhibiting a steady decrease in surface water availability, with reductions ranging from 5% to a maximum of 20% over the future time horizon. In various geographical areas, the average percentage change often falls within -10% to 10%. These variances mostly rely on the specific geophysical characteristics of each region.

A significant decrease in water demands for electricity production is evident from the results in the Resilience scenario. The leading cause of this global decline, varying between 40 and 60%, can be attributed to the assumptions made for mitigation efforts, specifically the decrease in fossil fuel consumption resulting in a reduced need for water-intensive cooling technologies in thermal power plants. The observed substantial decline in the irrigation and electricity sectors directly influences the levels of water stress experienced within the region. The results indicate a decrease in the

population's exposure to water stress in the Resilience scenario. According to the Baseline scenario projected for the year 2050, it is estimated that approximately 65-70% of the global population will experience water stress. However, this percentage is expected to fall to 48-52% under the Adaptation scenario and even lower to 45-50% under the Mitigation scenario (Resilience scenario), indicating the benefits of climate change adaptation.

As we approach the middle of the century, the vulnerable population in terms of access and risk in EWL sectors shows synergies with the Resilience scenario. According to the 2020 baseline, approximately 75% of the population had access to safe drinking water. In the Resilience scenario, this number is projected to increase to 95%, compared to 85% in the Baseline scenario. The proportion of the population that relies on solid fuels is projected to decline from 16.6-22.5% in the Baseline scenario to 5.9-6.3% in the Adaptation scenario and 5.3-6.0% in the Resilience scenario. In addition, the risk of hunger is anticipated to decrease from 2.4-2.8% in the Baseline scenario to between 0.05-2.19 and 0.02-2.24 % in the Adaptation and Resilience scenarios, respectively.

Regarding access to safe cooking, both the Adaptation and Resilience scenarios foresee substantial improvements, with approximately 96% of the population gaining access. While access to safe drinking water and cooking facilities aligns with SDGs 6 and 7, the model's reductions in hunger risk and reliance on solid fuels are distinctive benefits. These results highlight the effectiveness of resilient strategies in vulnerable communities and the significance of targeted interventions for equitable resource distribution.

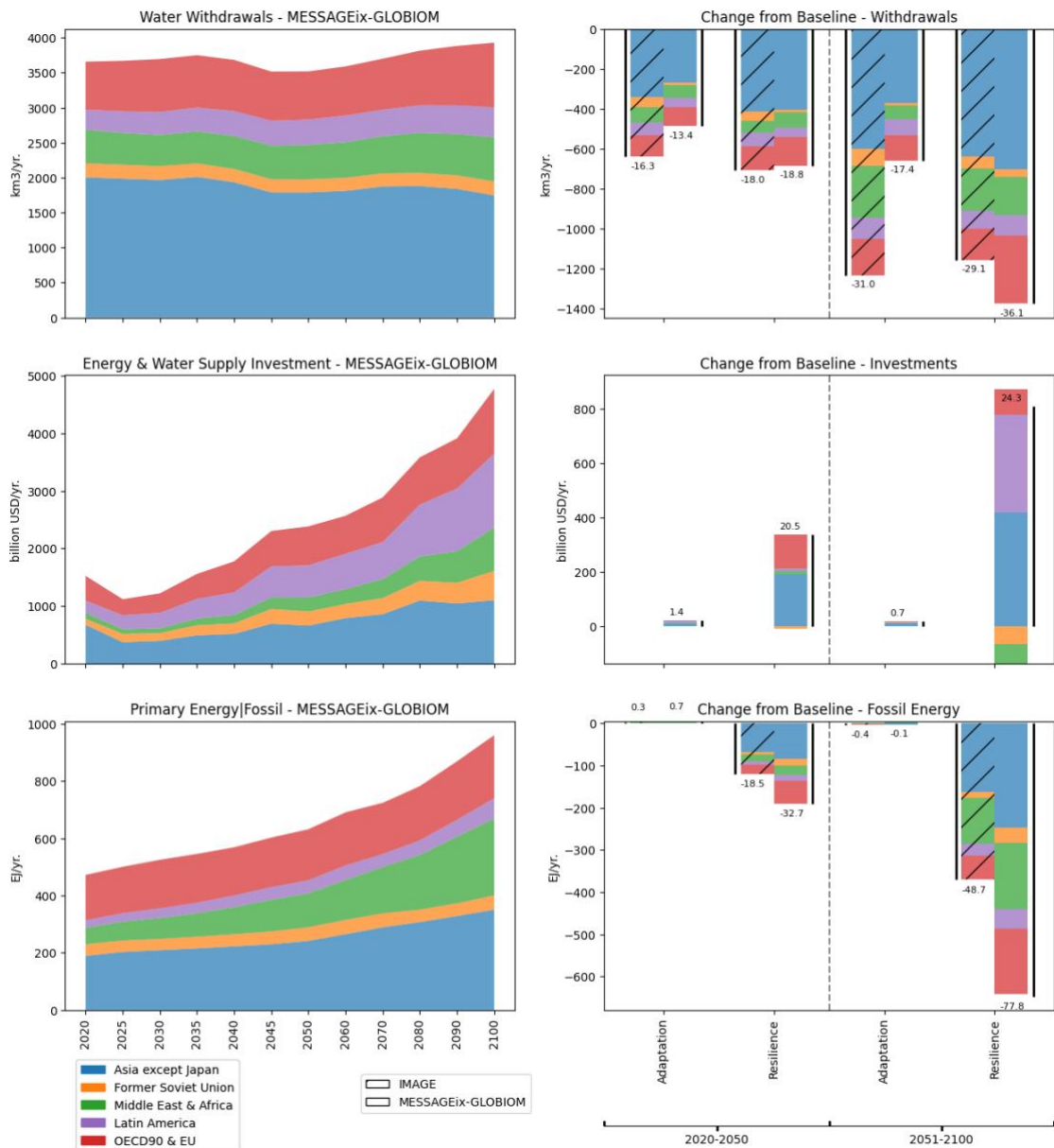


Figure 4.2 Summary of key indicators (Water Withdrawals, Energy & Water Supply Investment and Primary Energy Fossil use). The plots on the left hand side represent baseline values from MESSAGEix-GLOBIOM across the time horizon aggregated across the regions. The panels on the right shows the absolute changes as reported by both MESSAGEix-GLOBIOM & IMAGE. The text above each bar shows total percentage difference from the baseline. The results are averaged across 2020-2050 and 2051-2100 to show the outlook of pre and post mid century. The black lines indicate the net global absolute changes.

4.4 Water Supply portfolios of basins under Resilience & Reliability

Considering the increasing challenges on global water systems, it is crucial to understand the costs (investments and operational) associated with water supply from the pathways of IAMs that have often been overlooked in global climate assessments.

We present an in-depth analysis of the average annual water infrastructure costs for global basins and, as a summary, that the global costs associated with the Resilient scenario (535 billion USD/yr.) exceed those of the adaptation (527 billion USD/yr.) by just 1.5% thus suggesting that a CDR pathway is concurrent with the adaptation

pathway in terms of water supply costs. At the same time, the CDR pathway incurs fairer allocation of water resources and ensures fulfilment of climate policy targets.

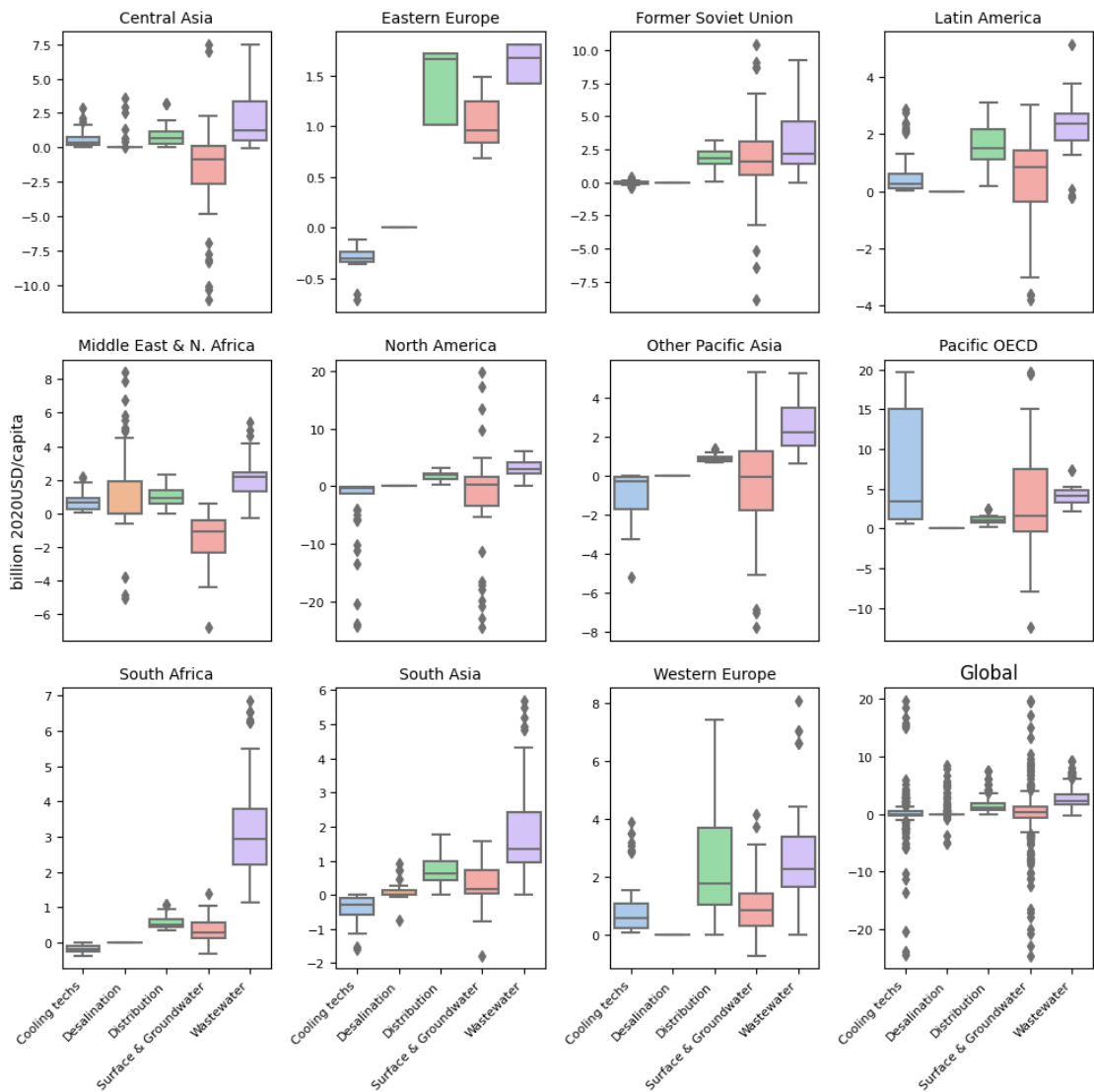


Figure 4.3 Distribution Average annual cost in billion US2020\$/capita by water commodities for Resilient scenario across different basins within each region (box plot refers to the basins within each region). These are the differences from the Baseline thus showing additional cost required to achieve Resilient pathway. The negative values here refers to the benefits in terms of cost (lesser cost than Baseline). The costs include operational and investment costs from MESSAGEix-GLOBIOM. Water distribution costs for providing water to municipal and industrial services, access to clean drinking water. Wastewater includes wastewater collection, treatment, recycling, and reuse costs. Desalination includes aggregated costs for membrane and distillation desalination technologies. Surface & groundwater refers to the extraction costs. These costs refer to long term average of the whole-time horizon.

Scaling these costs in terms so socioeconomics helps to understand the meaning of these costs. Our results find that in the resilience scenario, it is evident that North America and Western Europe exhibit the highest per capita cost for water supply (141 & 86 USD/capita on average). However, scaling to GDP, it becomes apparent that South Asia bears the most significant burden when these expenses amount to 0.05% of the regional GDP. In comparison, Sub-Saharan Africa lags with costs equivalent to 0.02% of its GDP. Further insights reveal that Africa has a notable

cost increase, rising from 14.85 USD per capita (2020-2050) to 48.9 USD per capita (2060 onwards) through the time horizon. Despite facing increased demands for water, these areas are also hindered by limited adaptive capacity, making it challenging to invest in resilient pathways. Moreover, some basins, such as the Rift Valley, Africa North Interior, Caspian Sea East Coast, Irrawaddy Salween Sittang, Arabian Sea Coast, Amazon, Australian Sea Cost, Niger, and Ganges Brahmaputra in the Central Asian region, show lesser costs of resilience pathway as compared to Baseline thus implying economically beneficial compared to other sectoral synergies.

To understand the complex dynamics of water supply systems from different sources, we summarize some insights from major river basins. We focus on the Resilience scenarios and understanding how it changes across the water supply reliability levels to account for variations in renewable water supply levels under climate change impacts.

The Congo Basin stands out as a case in point where wastewater reuse, though accounting for a mere 9% of the total water withdrawal (approximately 65 km³.yr), bears a disproportionately large burden of the costs, representing an astounding 85% of the total. This discrepancy underscores the economic intricacies and challenges inherent in wastewater reuse.

Results from The Ganges Brahmaputra basin show approximately one-third of the entire water supply originates from surface and groundwater sources, whilst the utilization of wastewater for reuse purposes accounts for around 8% of the overall water withdrawals. Significantly, when there is a substantial need for a reliable water supply, the proportion of water derived from wastewater reuse increases from 5%. Despite the increase in usage, the accompanying investment needs remain notably significant.

Results from Indus River Basin show insights into how the pressure on freshwaters can be effectively distributed to alternative water sources. The significant water stress experienced in this region has consistently resulted in limited access to freshwater resources. The limited availability of water resources necessitates transitioning towards other sources, such as desalinated water, estimated to be roughly 0.4 cubic kilometers per year. Notably, the landscape changes according to different scenarios of trustworthiness. In situations characterized by low reliability, there is a lack of substantial shift towards the utilization of desalinated or unsustainable groundwater sources. In contrast, when considering situations requiring high

reliability levels, the data presents a contrasting perspective, indicating a significant inclination towards utilizing alternative water sources such as desalination and brackish water. These sources are employed to fulfill the water demands, amounting to around 76 cubic kilometers per year.

Under the Resilience scenario, the North Colorado Basin also presents an alternate perspective, demonstrating a shift towards alternative water sources. This is seen in the significant growth in the utilization of desalination, which is projected to double by the middle of the century.

All basins show declining trend in investments pertaining to cooling systems. The decrease in the trend can be ascribed to the less dependence on fossil fuels within the energy composition as outlined in the Resilience scenario. For example, in the Danube Basin, it is noteworthy to observe a significant decrease of 70% in energy consumption for water under the Resilience scenario compared to the Baseline.

Water distribution costs holds significant portion in the overall cost portfolio. In the Resilience scenario, in contrast to the Baseline scenario, the higher costs observed in many basins serve as evidence of the collaborative endeavors aimed at guaranteeing reliable and clean drinking water availability, as well as establishing secure piped connections in both industrial and residential sectors.

We compared the governance projections from (Andrijevic et al., 2020b) to see the actual adaptive capacity of the basins. For example, The Ganges River, possessing a governance value of 0.6, demonstrates a moderate ability to adjust to these alterations.

However, this indicates the need for further endeavors to achieve comprehensive governance. When we compare African basins such as Lake Chad, Niger, Congo, and Tigris Euphrates with those located in the northern regions of the world, the investment needs results should be interpreted carefully. Although the investments needed in the African basins may seem relatively small, the average governance ratings of around 0.5 indicate much less capacity to adapt to a resilient future. These basins encounter significant challenges in their efforts to adapt to a resilient future, primarily because of political, economic and governance limitation. The noticeable deficit in adaptation within these basins serves as a clear indication of their susceptibility to the impacts of climate change and the need for effective strategies to enhance their resilience.

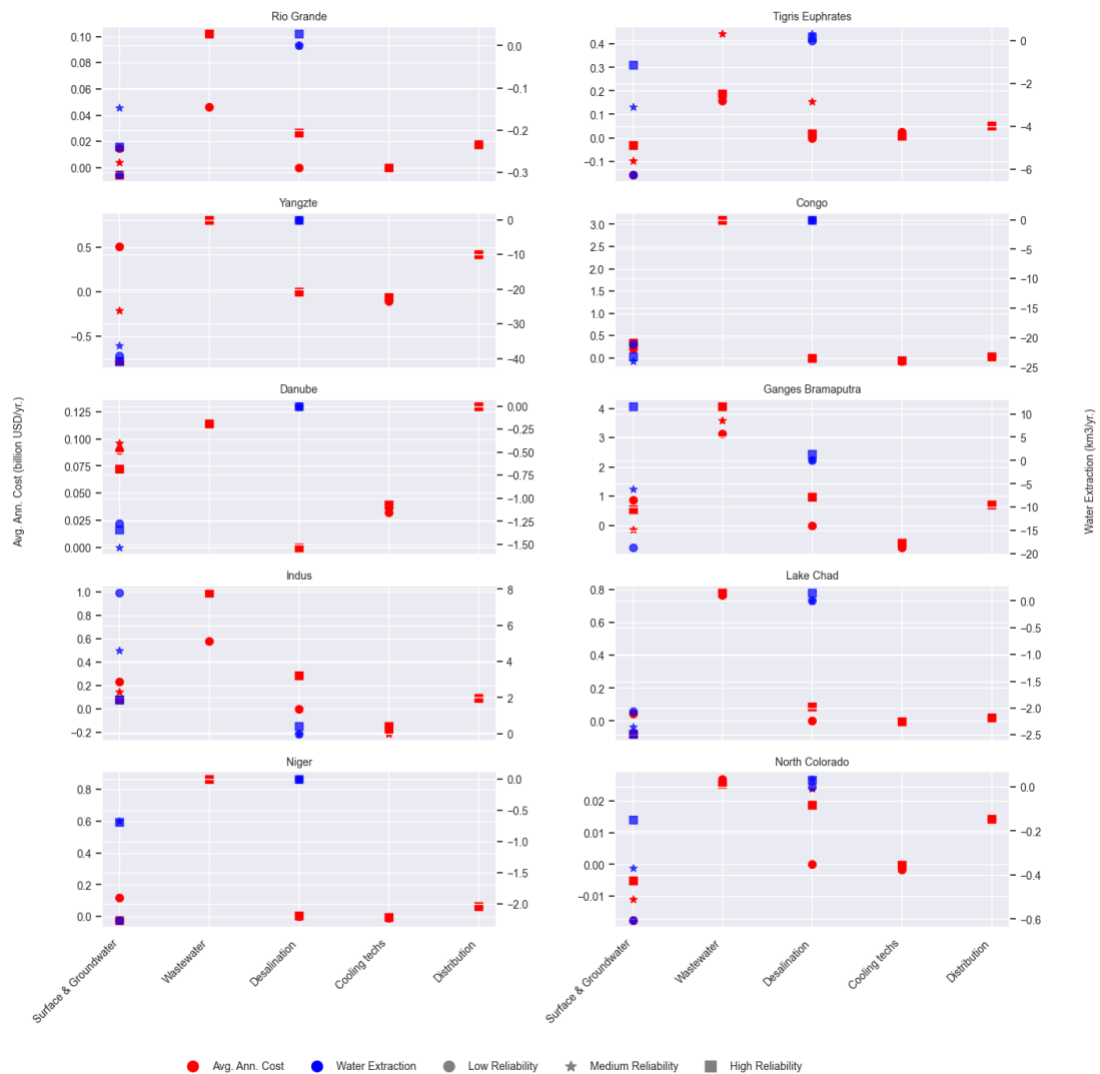


Figure 4.4 Absolute difference of Water Extraction (km³/yr.) & Average Annual costs (billion USD/yr.) from Baseline scenario for selected river basins. These differences show the variation of the indicators across the reliability scenarios.

On the other hand, regions such as North Colorado, despite facing water scarcity, exhibit good governance practices, which place them in a favorable position for the development of a resilient water system. In conclusion, it is crucial to acknowledge the inherent limitations in directly comparing investment levels across different basins. For example, the investments in Niger may not be directly comparable to those in the Danube region because to the varying levels of adaptive capacities. The deficiency in adaptation hampers the readiness of specific basins in facing the imminent difficulties posed by climate change and the endeavor to establish paths for resilience. As we navigate our path ahead, these findings emphasize the necessity of customized strategies that consider the distinct problems and capabilities of each basin.

4.5 Conclusion

Our study outlines the pivotal role of water system within the overarching framework of global climate narratives and uses multi sectoral IAM scenarios to support the analysis. The increased demand for long-lasting water infrastructure is what is responsible for the increased expenses shown along the Climate Resilient Development Pathway. The long-term benefits gained from effective water management synergies outweigh the short-term, albeit heavy, cost consequences. Notably, these anticipated costs could change depending on dynamic factors, such as changes in governance levels or advancements in technology, which could have an impact on GDP.

This analysis combines conceptual and quantitative explanations laying the groundwork in the nexus of water management and climate exigencies. Simply focusing on transformational adaptation would be myopic; instead, wise investments in the Climate Resilient Development Pathway would highlight our capacity for adaptation while reducing overall costs. A resilient future can be obtained by the convergence of sustainable development, climatic resilience, and human welfare.

The granularity of this discourse should be expanded in additional studies in order to emphasize and widen the dimensions of our findings. This work is a groundbreaking effort that creates a solid foundation for a sophisticated knowledge of sustainable water stewardship in the face of growing climatic uncertainties.

4.6 Methods

MESSAGEix-GLOBIOM 1.1_w

The MESSAGEix-GLOBIOM Integrated Assessment Model (IAM) developed from the MESSAGEix framework, an open-source environment designed to optimize energy systems. It also integrates macro-economic feedback via a stylized computable general equilibrium model (Huppmann et al., 2019).

This optimization is carried out iteratively in collaboration with MACRO, a macroeconomic model for a particular sector. MACRO provides projections of the macroeconomic demand response resulting from the MESSAGEix-calculated costs of energy systems and services.

The MESSAGEix-GLOBIOM_1.1_W version introduces new water modules, which include hydrological variables and a comprehensive representation of water supply and demand. These modules establish a connection between the MESSAGEix

energy system and the GLOBIOM land system. The module includes representation of biophysical climate impacts (Awais et al., 2023).

The MESSAGEix-GLOBIOM Integrated Assessment Model (IAM) was expanded to include a sector-specific representation of the water system and climate impact. MESSAGEix-GLOBIOM v1_w, the newest version of the model, incorporates endogenous spatial and temporal explicit water allocation mechanisms. These mechanisms simultaneously determine energy, land use, and water needs, taking into consideration the influence of constraints such as limited water availability on the utilization of energy and land use resources (Awais et al., 2023).

The model consists of a framework capable of linking any Global Hydrological Model (GHM) output. In this case, the data from the CWatM global hydrological model (Burek et al., 2019) were used. A spatial layer with a higher resolution was incorporated into the IAM to preserve relevant hydrological information. Using the basin delineation provided by the HydroShed Database (Lehner & Grill, 2013), the model comprises 210 basins.

The water sector information is mapped to the eleven global regions of the MESSAGE energy system IAM, allowing the translation of relevant hydrological information to the energy sector and vice versa. The framework balances water supply and demand at the basin level while delineating water needed for energy and land use at the level of MESSAGE R11 regions.

MESSAGEix-GLOBIOM Nexus tracks annual municipal and industrial water demand, water required for power plant cooling technologies, water used in energy extraction, and irrigation water use. It achieves this by supplying water from a variety of sources, including surface water, groundwater, and desalinated water. In addition, it includes a wastewater treatment infrastructure for tracking water volumes in the wastewater system and estimating the investments necessary to meet various treatment objectives. Future integrated analyses of climate feedbacks and adaptation pathways are made possible by monitoring the water demands across urban and rural dimensions. To account for the feedbacks of various RCP forcings within the IAM, climate feedbacks are integrated across water availability, desalination potential, hydropower potential, and land-use variables (bioenergy, water for irrigation) (Awais et al., 2023).

IMAGE 3.2

The Integrated Assessment Model (IAM) framework of IMAGE (D. van Vuuren et al., 2021) simulates the global and regional environmental effects of alterations in human activity. The IMAGE model includes comprehensive descriptions of the energy and land use systems. It simulates the majority of socio-economic and environmental parameters for 26 regions based on a geographical grid of 30 by 30 minutes or 5 by 5 minutes (approximately 50 km and 10 km at the equator, respectively). IMAGE is designed to assess large-scale and long-term interactions between human development and the natural environment and to identify response strategies to global environmental change by evaluating mitigation and adaptation options.

The IMAGE 3.2 model has been completely calibrated through 2015, with some variables calibrated through even more recent years (2018 for energy system variables and 2020 for renewables capacity and CO₂ emission data). The model includes the economic effects of the Covid pandemic in recent years. In IMAGE 3.2, the base year for scenario analysis is 2020, implying that scenarios follow the same trajectory from 2015 to 2020. The modeling of energy demand has been enhanced, particularly in end-use sectors such as transportation, industry, structures, and services.

The model contains technology descriptions for each industry segment. In addition, bioenergy modeling has been considerably improved by incorporating dynamic land-use change emission factors based on the IMAGE-land model and introducing biofuel production with carbon capture and storage technology pathways.

The number of produce categories in the land use sector was increased to 16, representing all FAO-reported crop production. Based on FAO data and ESA-CCI satellite data, deforestation caused by factors other than agricultural expansion has decreased. Concerning climate change effects and exogenous and endogenous trends in crop yield changes, the link between the agriculture-economic model MAGNET and the IMAGE model was significantly enhanced.

The modeling of land-based Mitigation in IMAGE and MAGNET has been improved to account for avoided deforestation and afforestation, as well as the interaction between non-CO₂ mitigation and the agriculture and food system. The water modeling in IMAGE that is linked to LPJmL was enhanced by incorporating municipal, energy, and industry water demand into LPJmL, allowing environmental

flow requirements to be accounted for. The marginal abatement cost contours for all greenhouse gases other than CO₂ have been updated based on recent research.

Scenario Assumptions

Both models are differently structured, so we present results where they are available; otherwise, show the available ones for each model. However, the scenarios were designed based on common assumptions.

Socio-economic Assumptions

All scenarios include Shared Socio-economic Pathway 2 SSP2. The population and GDP projections have been upscaled from the gridded data onto the required regional definitions.

Time Horizon

All scenarios include the time horizon until the end of century.

Climate

Table 4.1 presents a summary of biophysical impacts included in both models.

SDGs

Table 4.2 presents summary of SDG assumptions in both models

Table 4.1. Included climate impacts and underlying approach/data

Biophysical climate impacts	Approach
Renewable supply (hydro)	Renewable costs supply curves based on 0.5x0.5 grid calculations (Gernaat et al., 2021). MESSAGEix -GLOBIOM uses hydropower cost supply curves only.
Heating/cooling demand	Impact via population-weighted heating and cooling demands based on the work of (Byers et al., 2018; Mastrucci et al., 2021) 0.5 x 0.5 grid
Water availability	Runoff and groundwater recharge from CWatM calculated at 0.5 x 0.5 grid (Burek et al., 2020) for MESSAGEix-GLOBIOM. IMAGE 3.2 uses LPJmL hydrological model outputs (Schaphoff et al., 2018)
Crop yields	Climate impacts on crop productivity, nitrogen, and irrigation from the CMIP6 projections of the crop-model EPIC-IIASA are used in GLOBIOM. EPIC-IIASA estimates the impact of climate on rice, maize, wheat, and soy and feeds into GLOBIOM following (Müller & Robertson, 2014) IMAGE uses crop yield outputs from LPJmL (Schaphoff et al., 2018)
Cooling technology capacity factor	Climate impacts on cooling water discharges for cooling technologies of fossil power plants are used from (Yalew et al., 2020b) only in MESSAGEix-GLOBIOM.
Desalination potential	Desalination potential climate impacts are based on water stress outputs from the combinations of GHMs & GCMs from (Byers et al., 2018) only in MESSAGEix-GLOBIOM
<p>1 IMAGE uses IPSL-CM5A-LR climate model.</p> <p>2 MESSAGEix-GLOBIOM uses GFDL-ESM2M (for water availability), UKESM1-0-LL (for crop yields), and HadGEM2-ES (for heating/cooling demand). This choice has been motivated by the preferences from different models itself.</p>	

Table 4.2 Sustainable Development Goals
SDG Measure - IMAGE

Measure - MESSAGEix-GLOBIOM

SDG2 - Hunger	Change towards a healthy diet.	
	Transition towards healthy diets including reduced meat consumption, healthy total calorie intake and increased vegetable intake following (Willett et al., 2019).	<ul style="list-style-type: none"> • < 1% undernourishment goal by 2030 • Decrease of animal calorie intake to 430 kcal/capita/day by 2030 (USDA recommendations for healthy diets)
SDG6 - Water	Reduce food waste.	
	High income countries and middle-income regions reduce food waste to the lowest level among them, in three food supply chain stages (primary, processing, consumption), for six commodities groups (cereals, roots and tubers, oilseeds and pulses, fruit and vegetables, milk, meat)	50% reduction in food waste compared to SSP2 assumptions
	Efficiency improvement for irrigation:	
	Not included	Limited irrigation water consumption in agriculture to sustainable removal rates that do not jeopardize ecosystem services and environmental flows (Frank et al., 2021a)
	Efficiency improvement for electric power generation:	
	-59% in 2050 compared to a baseline case based on (D. P. Van Vuuren et al., 2019)	Not included
	Implement environmental flow constraints.	
	Based on the variable monthly flow (VMF) method developed by (Pastor et al., 2014b, 2019a) where 60%, 45% and 30% of the mean monthly natural flow is reserved for ecosystems in low, intermediate and high flow periods, respectively.	Based on the variable monthly flow (VMF) method developed by (Pastor et al., 2014b, 2019a) where 60% and 30% of the mean monthly natural flow is reserved for ecosystems in low and high flow periods, respectively.
	Efficiency improvement for industry:	
	-5% in 2050 compared to a baseline case based on: (D. P. Van Vuuren et al., 2019)	Not included
Universal piped water access, wastewater collection and improved wastewater treatment capacity		
Not included	Minimum of half all return flows are treated by 2030 for developed regions and 2040 for developing regions.	
SDG7 - Energy	Maximized electricity access	
	On-grid electrification only, based on SSP1 (D. van Vuuren et al., 2021) assumptions (98% in 2030).	Results from the MESSAGEix-GLOBIOM are iterated through the MESSAGE-Access-E-USE (end-use services of energy) model by provision of access targets based on income levels and GDP pathways and population with access to modern energy access and the energy demand adjustments are calculated.
	Minimized traditional bio and coal in cooking and heating	
Based on SSP1 assumptions (90% reduction of traditional bio in 2050)	90 % access target to modern cooking energy for cooking by 2030	
SDG15 (Life on land)	Implement protected land maps	
	As in SSP1 (+/-30% protected) (D. van Vuuren et al., 2021)	Based on (Frank et al., 2021b), 34% protection in 2030 was assumed and additional area based on the UNEP-WCMC Carbon and Biodiversity Report to identify highly biodiverse areas and prevent their conversion to agriculture or forest management from 2030 onwards.

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Chapter 5 Conclusion

Integrated Assessment Models (IAMs) need a comprehensive framework that integrates the water sector and climate impacts, as detailed in Chapter 1 and section 3.1 to understand the IAM responses from the climate impacts. This thesis has made significant progress by introducing a new global framework of the Integrated Assessment Model MESSAGEix-GLOBIOM; MESSAGEix-Nexus. A summary of each chapter is outlined below;

The Indus Delta Case Study (Chapter 2)

The Indus River Basin (IRB) is challenging in managing water resources, socio-economic inequalities and climate vulnerability. The findings emphasize the significance of adaptive management techniques and the "learning by doing" methodology. The allocation of environmental flows (EF) is not only a technical challenge but also necessitates stakeholder negotiation to ensure a river basin's sustainability. In light of the vulnerability of the IRB to climate change, this chapter emphasizes the imperative need for on-site experiments to establish environmental flow standards. In addition, the ambiguity of the local policies highlights the need for explicit guidelines to ensure equitable water distribution, promoting socio-economic development and delta replenishment.

MESSAGEix-Nexus framework (Chapter 3)

A new framework is developed in order to fulfill the research gaps in the IAM scenarios, allowing for a more comprehensive examination of biophysical climate impacts and water constraints at multiple scales. The newly developed nexus module provides a more nuanced representation of water sector interactions, harmonizing supply and demand at global basin scales. Increasing water supply dependability necessitates investments in alternative water sources with a cost. Furthermore, the framework allows regional insights into Energy Water Land resource constraints, capacity installations and associated costs. In addition to highlighting the profound effects of climate change on power generation, the study emphasizes the responses on how including climate impacts affects the result. For example, a significant reduction in crop yield is observed as adaptation response. This reduction then impacts the water withdrawals and subsequently the associated water supply needs. The model's flexibility and

reproducibility make it a valuable resource for policymakers around the globe, enabling rapid prototyping and addressing EWL nexus dynamics in terms of cost and structural change for the global or regional assessments.

Understanding Water System Boundaries (Chapter 4)

Water systems are integral to climate narratives on a global scale. Along the Climate Resilient Development Pathway, the multisectoral multi-model (MESSAGEix-GLOBIOM & IMAGE) IAM scenarios have highlighted the rising costs of long-term water infrastructure investments. However, the long-term benefits of effective water management synergies justify these costs. It is essential to recognize that these costs are dynamic, influenced by factors such as changes in governance and technological progress. The research demonstrates that while looking at the results from IAMS, comparing results with socio-economic inequalities helps to understand the adaptation needs more effectively. It also highlights the overlapping of Sustainable Development Objectives with the Mitigation which should be a preferred future pathway to policymakers. This chapter lays the groundwork for a more comprehensive comprehension of sustainable water stewardship in escalating climatic uncertainties.

The applications of the MESSAGEix Nexus framework are delineated separately to underscore their distinct significance apart from the insights provided:

- The framework facilitates a global, integrated EWL nexus policy assessment. With energy and land segmented into 11 regions and the water sector encompassing 210 basins, this framework can provide in-depth regional and global insights, demonstrating potential future pathways under a variety of climate and socio-economic assumptions.
- The framework is also flexible to consider different hydrological and climate model combinations to see the uncertainties of different climate models however this is computationally expensive.
- By comparing scenarios with and without climate impacts, the framework allows to distinguish adaptation responses across diverse sectors, thereby providing a clearer picture of potential challenges and solutions of climate impacts. Moreover, scenarios with single sector impacts and single development objectives helps to understand more robust insights onto responses of the system to a single sectoral shift. (see section 3.5).

- By integrating both mitigation and adaptation strategies, the framework portrays a comprehensive picture of potential resilient futures and provides a road map for navigating the challenges posed by climate change (Section 4.2).
- Among the distinguishing characteristics of the MESSAGEix Nexus is its nuanced depiction of the water sector. This granularity, which is frequently absent from IAM scenarios, provides greater insight into water supply sources, investments, and the larger dynamics of water management (section 4.3).

Limitations & Future Development

While the MESSAGEix Nexus framework has made significant advances in its representation of the water sector and biophysical climate impacts, it is essential to recognize its current limitations and plan for its future development.

The framework currently does not account for inter-basin or spatial unit transfers, which are crucial for addressing transboundary challenges in river basins. Another limitation is the lack of representation of water storage, particularly considering the significance of water management during high and low flow seasons. Although the flow percentiles approach has been implemented as a workaround, it only partially addresses this concern. Multiple data sources are utilized by the Nexus module to depict climate impacts, which can result in inconsistencies. In addition, the Global Hydrological Model's (GHM) sensitivity and uncertainty are more pronounced than those of climate models. When impacts are integrated, the current structure of the model implies an endogenous adaptation response, potentially oversimplifying the complex dynamics of the Energy-Water-Land (EWL) sectors. In addition, the framework does not account for climate extremes such as droughts, flooding, and heatwaves, nor their economic costs or macroeconomic feedbacks.

The following improvements are suggested to improve the robustness and capability of the framework and have not been addressed as part of this thesis:

- A broader spectrum of climate impact dimensions, e.g., including more biophysical climate, with a focus on a higher tolerance for statistical climate extremes at sub-annual temporal resolutions. Extreme impact representation will help better understand adaptation responses and capacities.
- Consistent climate assumptions across biophysical climate impacts will help reduce the uncertainties of different model projections and uncertainties.

Climate extremes such as droughts, floods, cyclones, and sea-level rise will be incorporated alongside the seasonality and variability of water resources.

- The framework is proposed to be refined to also account for economic damages because of climate change, which can help understand the economic constraints.

Appendix

Appendix A - Chapter 2

S1 Environmental flow assessment methods

The environmental flow assessment methodologies that are currently in use depend on linkages to other local policy recommendations and stakeholder engagement [1]. There are ongoing efforts in defining standards and methods to account for environmental flow methods in rivers based on the ecohydrological relationships in rivers [2]. More than 200 environmental flow assessment methods exist globally [3]. There are various literatures and studies for environmental flow assessment methods and practicality of methods for river users from hydrological (Tenant, Tessamann, etc.), hydraulic, habitat-simulation, holistic methods applied in several case studies and global scale hydrological models [4].

Tessmann method considers intra-annual variability of flow and assumes 20% of Mean Monthly Flow (MMF) in low flow season whereas 40% of MMF in high flow season, considering that $MMF \leq \text{Mean Annual Flow (MAF)}$ in high flow season and vice versa in low-flow season [5]. The Tennant method assumes that a certain portion of the Mean Annual Flow (MAF) is required for sustainable biological integrity of river systems. Tennant method was originally developed for North Central USA, therefore it also recommends the proportionate flow of MAF during low flow (20% of MAF) and high flow (All MAF) periods whereas it recommends a seasonal and temporal matching of low and high flow seasons [6]. The Variable Monthly Flow (VMF) method is based on the average monthly flow. This method accounts for the natural variability in river discharges on a monthly time step and adjusts environmental flow requirements based on the flow variations. This method was developed in addition to Tennant method to increase the protection of freshwater ecosystems, with different allocation percentages in low and high flows [4]. Another approach to assess environmental flow assessment being used in some case studies is flow duration curves, which define a proportion of time a certain flow threshold level is equaled or exceeded in the river or region. These include methods based on flow exceedance curves such as Q50, Q95, Q90 and etc. curves depending on monthly time-steps [7].

Another basic approach beside the minimum flow threshold methods and Statistical methods is Percentages of Flows (POFs) method. The standards defined in the USA, The European Union and elsewhere in the recent past are based on a POF approach which takes into consideration the variability of flows in a spatial and temporal scale. Also, POF approach is found to be a more protective than statistical methods and minimum flow

thresholds. [8].Richter [8] gave a concept of defining a Sustainability Boundary Approach (SBA) which could be developed around the natural flow conditions along the spatial and temporal scale. However, he argued that the decision of choosing the allowable percentage of depletion for a river is a socio-political decision as much as it is a scientific one. However, a presumptive standard to constrain the water withdrawals and dam operations was proposed to ensure and fulfill the environmental flow requirements in rivers. Richter [8] suggests that, if a high level of environmental protection is required, then the daily natural flow alterations should not exceed 10% for maintaining the natural structure and function of ecosystem services, whereas for a moderate level of protection 11-20% flow alterations are recommended.

Due to extensive groundwater pumping and poorly understood science and policies of groundwater management, Gleeson and Richter [9] proposed a presumptive standard for the contribution of groundwater suggesting that high levels of environmental protection can be achieved if monthly baseflow is reduced by less than 10% through groundwater pumping.

A group of international scientists presented a new framework, Ecological Limits of Hydrological Alteration (ELOHA). It constitutes different hydrological techniques and environmental flow methods, existing hydrological and ecological databases from different rivers that can help to develop scientific relationships between hydrological flow alterations and ecological responses. The framework is capable of classifying segments of rivers into different ecological classifications and subclassification according to geomorphological characteristics. However, the framework was meant as a more comprehensive implementation of sustainable freshwater on a global scale [10]. The framework needs many databases and efforts to produce and therefore seems more of an ideal framework than practical, applicable where flows are meant to be saving some particular species [11], [12].

S2 Methods

Table A-S1 Set of technologies in technology groups

Technology group	Technologies
Fossil energy	Coal, oil, gas
Renewable energy	Solar, wind, geothermal

Hydropower	River, canal, existing and planned hydropower power projects
Electricity grid	Electricity distribution and transmission
Nuclear	Nuclear technology
Water distribution	Diversion, distribution, wastewater collection, desalination, canal
Wastewater treatment	Wastewater recycling
Rural generation	Ethanol generation, solid biomass, unconnected pv pannels, diesel generators
Irrigation	Irrigation technologies

Table A-S2 Data sources used in NEST (adapted from Vinca et al.[13])

Parameter(s)	Dataset	Spatial Resolution	Latest Year
Country administrative boundaries	Database of Global Administrative Areas (GADM)	polygon	2008
Basin and subbasin boundaries	HydroBASINS database	polygon	2012
Climate forcing	Intersectoral Impact Model Intercomparison Project (ISIMIP)	$0.5^\circ \times 0.5^\circ$	2015
Urban and rural population	Jones and O'Neill (2016)	$0.125^\circ \times 0.125^\circ$	2010
Urban and rural GDP	Byers et al. (2018)	$0.125^\circ \times 0.125^\circ$	2010
Elevation, flow-direction, basin/lake boundaries	HydroSHEDS Database	$0.004^\circ \times 0.004^\circ$	2008
Non-hydro power plant capacity, age and location	World Electric Power Plant (WEPP) Database	asset-level	2017
Power plant cooling technologies	Raptis et al. (2016)	asset-level	2014
Hydro power plant capacity, age and location	van Vliet et al. (2016)	asset-level	2017
Reservoir capacity, age and location	Global Reservoir and Dam (GRanD) Database	asset-level	2014
Crop areas, yields and location	Global Agro Ecological Zones (GAEZ) Database	$0.1^\circ \times 0.1^\circ$	2005
Protected areas	World Database on Protected Areas (WDPA)	polygon	2014
Forests	Global Forest Change (GFC) Database	$0.004^\circ \times 0.004^\circ$	2014
Depth to groundwater	Fan et al. (2013)	$0.01^\circ \times 0.01^\circ$	2012
Historical energy supply and demand by sector	International Energy Agency (IEA)	national	2017
Historical water supply and demand by sector	Information System on Water and Agriculture (AQUASTAT)	national	2015
Historical irrigation water supply by source	Cheema et al. (2014)	$0.1^\circ \times 0.1^\circ$	2015
Historical non-irrigation groundwater use	Wada et al. (2016)	$0.5^\circ \times 0.5^\circ$	2005
Historical transmission capacity and roads	OpenStreetMap	asset-level	2017
Historical on-farm energy use incl. pumping	Siddiqi and Wescoat (2013); Rao et al. (2019)	provincial	2015
Historical water conveyance capacity	Estimated from technical reports	asset-level	2018
Historical crop prices, fertilizers and crop coefficients	Food and Agriculture Organization (FAO)	national	2018
Planned reservoir and power plant capacity	Estimated from technical reports	asset-level	2030
Power plant cost and performance	Parkinson et al. (2016); Fricko et al. (2016)	technology-level	2014
Surface and groundwater performance	Kahil et al. (2018)	technology-level	2010
Irrigation cost and performance	Local data collected	technology-level	2010
Wastewater cost and performance	Parkinson et al. (2016)	technology-level	2014
Desalination cost and performance	Parkinson et al. (2016)	technology-level	2014

Table A-S3 Calibration parameter values for convergence of Community Water Model (CWATM) (adapted from Vinca et al.[13])

Parameter	Value
Snowmelt coefficient	0.003597
Crop factor correction	1.211
Ice melt coefficient	0.5366
Soil preferential flow constant	5.4
ARNO b	1.259
Interflow part of recharge factor	1.807
Groundwater recession coefficient factor	3.823
Runoff concentration factor	1.492
Routing Manning's N	8.104
Reservoir normal storage limit	0.5257
Lake alpha factor	1.154
Lake wind factor Value	1.205

S3 Supplementary results

Nexus Synergies for SDG scenarios (previous analysis)

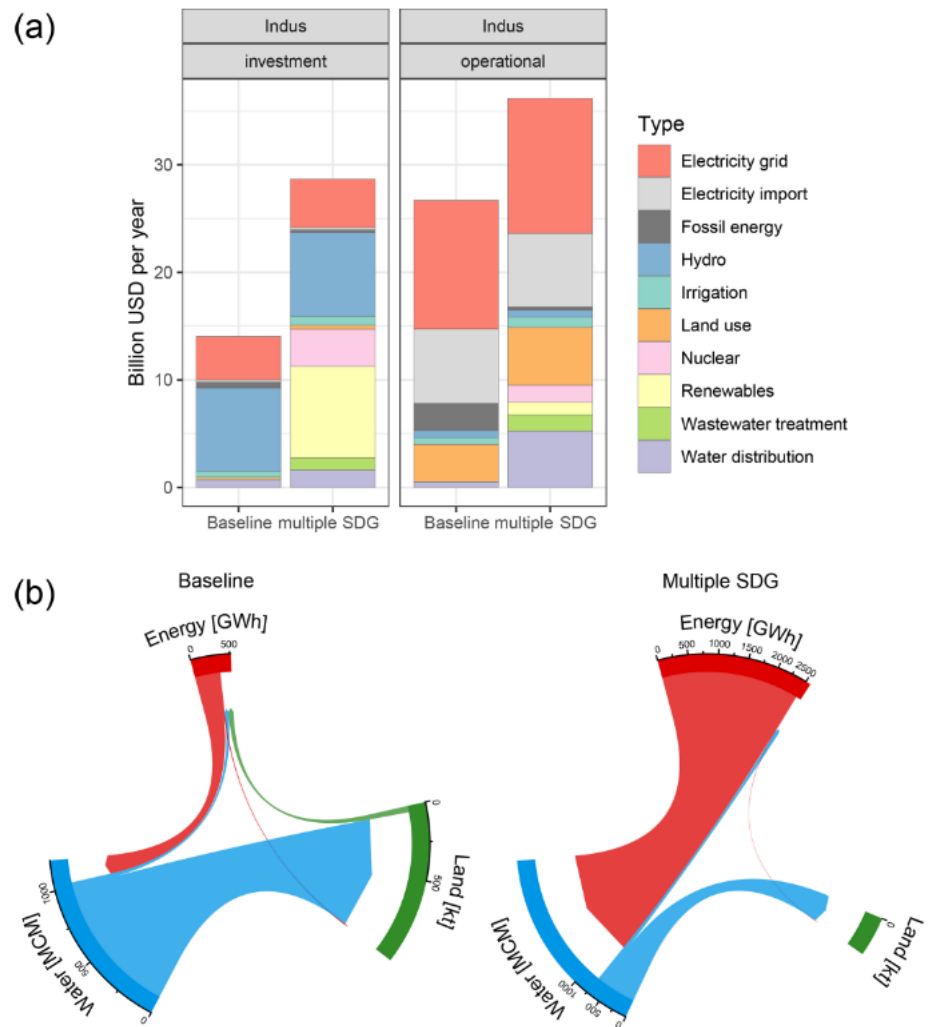


Figure A-S1 a) Comparison of investments (average yearly costs) for the entire basin across the baseline and multiple SDG scenario and **b)** representation of synergies across water, energy and land sectors from previous work by Vinca et al. [13]

Water sources & Withdrawals

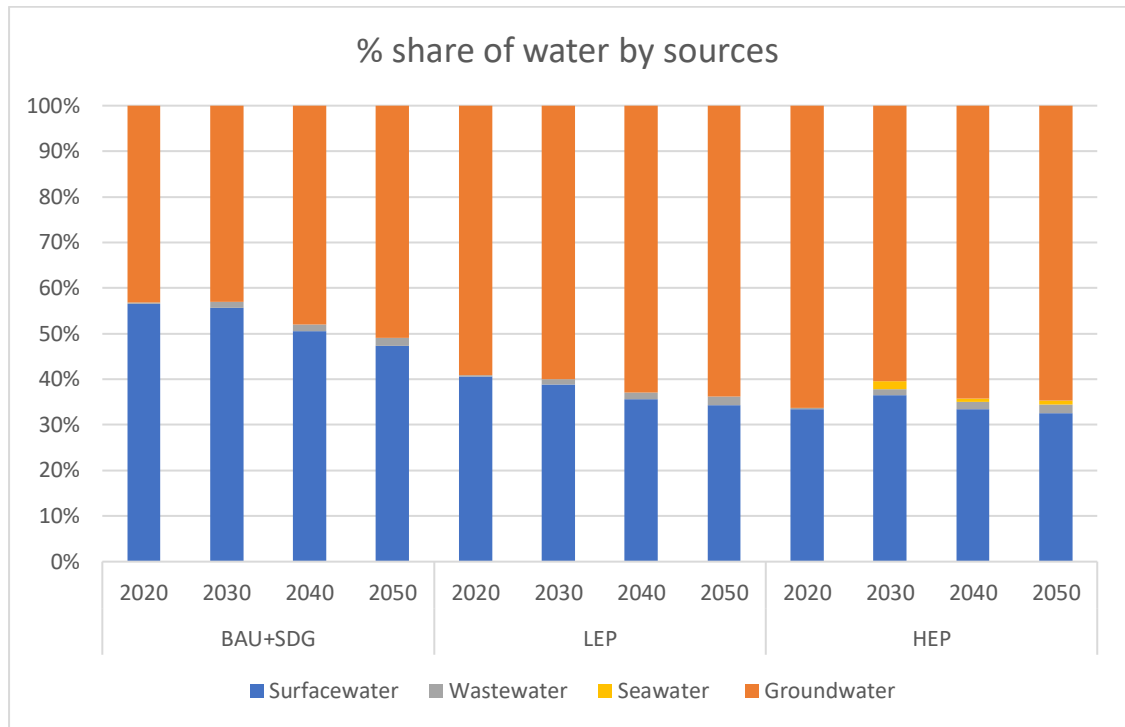


Figure A-S2 Percentage share of water sources

Nexus Interactions

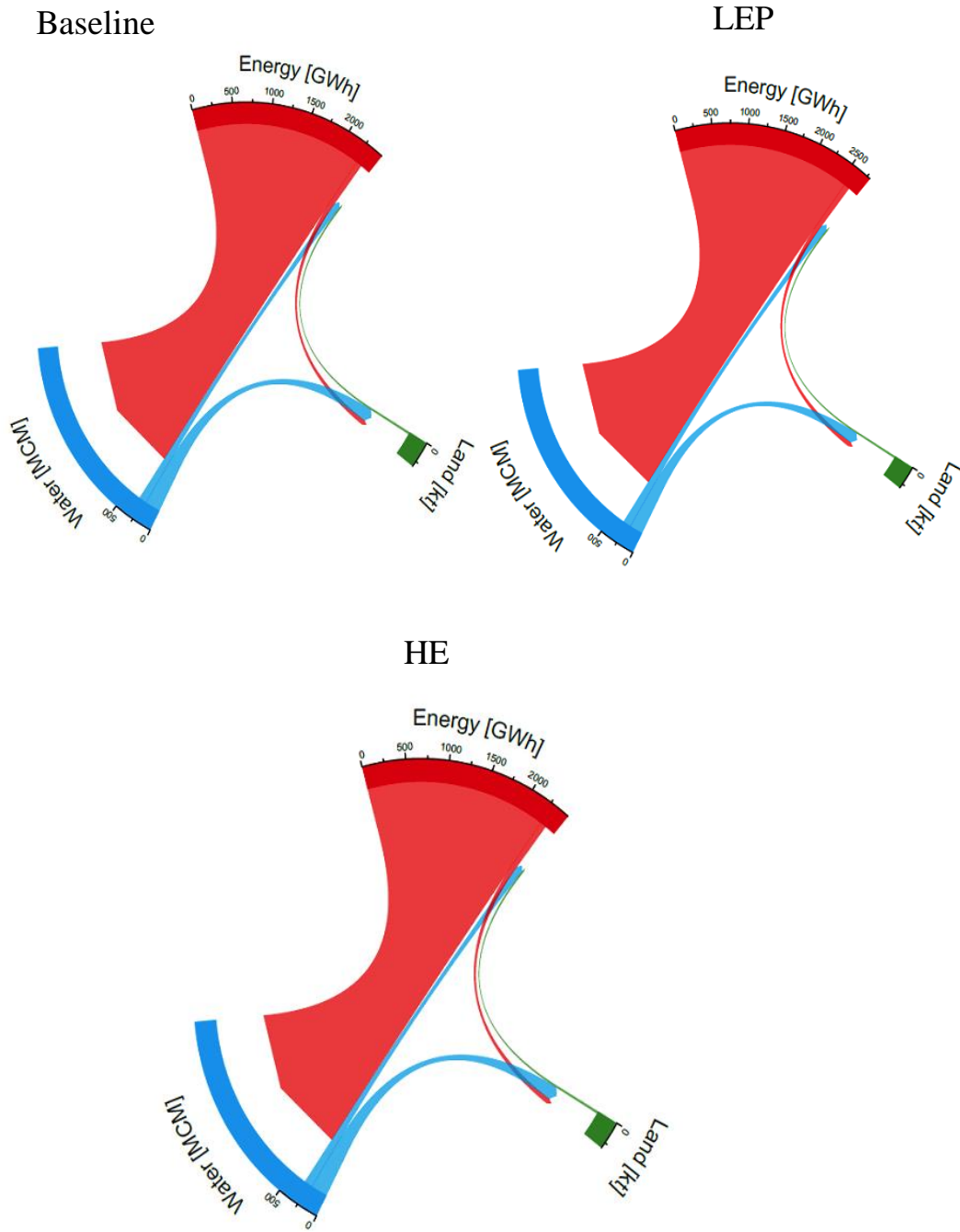


Figure A-S3 Nexus interactions for different scenarios

Table A-S4 Total Costs of sensitivity scenarios

Scenarios	Energy production	Hydro + Renewables	Irrigation	Land Use	Wastewater treatment	Water distribution	Total Savings	% savings from baseline case
Baseline AGRI0.9	-1.06	0.00	-1.08	-0.97	0.00	0.42	-2.69	-3.38
Baseline AGRI1.1	0.74	0.05	0.87	1.03	0.00	0.00	2.68	3.16
Baseline COOP	-3.03	0.15	-1.33	-1.92	0.00	-2.09	-8.22	-11.11
Baseline ELEC0.9	-4.28	6.77	-0.97	0.02	0.00	15.46	16.99	17.12
Baseline ELEC1.1	0.34	12.91	-1.05	0.02	0.00	15.45	27.68	25.18
Baseline EMISS	-4.74	8.44	9.21	-0.46	0.00	0.04	12.49	13.18
Baseline WASTEWTR	-3.24	8.54	-1.34	-0.40	0.00	1.13	4.69	5.39
LEP AGRI0.9	-3.22	8.70	-2.05	-0.94	0.00	1.94	4.43	4.41
LEP AGRI1.1	-1.97	9.28	-0.55	1.05	0.00	0.82	8.63	8.25
LEP COOP	-3.10	-0.21	-2.32	-2.56	0.00	1.49	-6.69	-7.49
LEP ELEC0.9	-6.39	5.67	-1.47	-0.05	0.00	-11.84	-14.09	-17.20
LEP ELEC1.1	-2.06	11.74	-1.54	-0.05	0.00	-11.85	-3.76	-4.08
LEP EMISS	-4.66	8.79	8.94	-0.51	0.00	-0.35	12.21	11.28
LEP WASTEWTR	-2.71	8.90	-1.79	-0.47	0.00	4.70	8.62	8.24
HEP AGRI0.9	-3.47	9.33	-2.62	-0.93	0.00	0.69	3.00	2.19
HEP AGRI1.1	-1.53	9.84	0.37	1.03	0.00	1.25	10.96	7.56
HEP COOP	-3.90	-0.11	-4.04	-3.27	0.00	-7.84	-19.16	-16.69
HEP ELEC0.9	-7.82	6.24	-2.70	-0.05	0.00	-33.43	-37.76	-39.23
HEP ELEC1.1	-3.15	12.38	-2.78	-0.06	0.00	-33.42	-27.03	-25.27
HEP EMISS	-4.73	9.50	8.87	-0.55	0.00	0.47	13.56	9.19
HEP WASTEWTR	-3.81	9.65	-2.57	-0.50	0.00	4.61	7.38	5.22

A - Supplementary Bibliography

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Appendix B - Chapter 3

S1 Scales – Spatial & Temporal

The detailed methodology of spatial and temporal aggregation is mentioned in the main text. However, the following table provides additional details and steps used in post-processing the gridded data for use in nexus module. Also, the bias adjustment of the data is done for the different scenarios of the data basically to keep the 2020 year same. Then the difference between both scenarios is applied over the time series as the adjustment in the base year (See Step 4 below). The names of B210 basins and their mapping with R11 region can be found in the model folder (data/node/B210_R11.yaml)

Table B-S1 Steps used to process the gridded data within the nexus module

Step No.	Scale	Input	Output	Procedure
1	Spatial	gridded	gridded	Convert kg/m2/sec to km3/ yr. and moving monthly average
	Temporal	monthly	monthly	
2	Spatial	gridded	basin	Spatial sum of grid values over basin
	Temporal	monthly	monthly	
3	Spatial	basin	basin	$Val_{2020} = (\text{avg. } val_{2015-2030 \text{ rcp } 2.6} + \text{avg. } val_{2015-2030 \text{ rcp } 60})/2$ Val ₂₀₂₀ is applied to all data frames at this point. Val ₂₀₂₀ is monthly 2020 data
	Temporal	monthly	monthly (same 2020 value for rcp scenarios)	
4	Spatial	basin	basin	Monthly bias correction is applied for each rcp value to adjust for the previous step. The bias correction is only done at 5 year intervals monthly data. For the 5 year average, MESSAGEix time step formulation is used such that for example ; $val_{2025} = (val_{2021} + \dots + val_{2025})/5$ Now for val ₂₀₂₅ , bias correction is done as; $delta_{rcp6} = \text{avg. } val_{2015-2030 \text{ rcp } 6} - val_{2020}$ $delta_{rcp2.6} = \text{avg. } val_{2015-2030 \text{ rcp } 2.6} - val_{2020}$ $val_{rcp6 \text{ bias corrected}} = val_{rcp6} + delta_{rcp6}$ $val_{rcp2.6 \text{ bias corrected}} = val_{rcp2.6} + delta_{rcp2.6}$ the delta is reduced by 0.2 in each 5 year interval until the delta reaches zero in 2045
	Temporal	monthly	monthly bias corrected	
5	Spatial	basin	basin	5 year monthly data is prepared from monthly bias corrected data by just filtering the 5 year timesteps (2020,2025,...) from the previous step
	Temporal	monthly bias corrected	5 year monthly	
6	Spatial	basin	basin	Three reliability scenarios are created; val _{q50} , val _{q70} , val _{q90} by taking quantiles of monthly bias corrected data .
	Temporal	monthly bias corrected	5 year annual	

S2 Water Resources

Some selected basins are shown here as an example. However complete data can be accessed in the GitHub repository under [data/water/availability](#) where all of the post-processed hydrological data are available.

S2.1 Hydrology

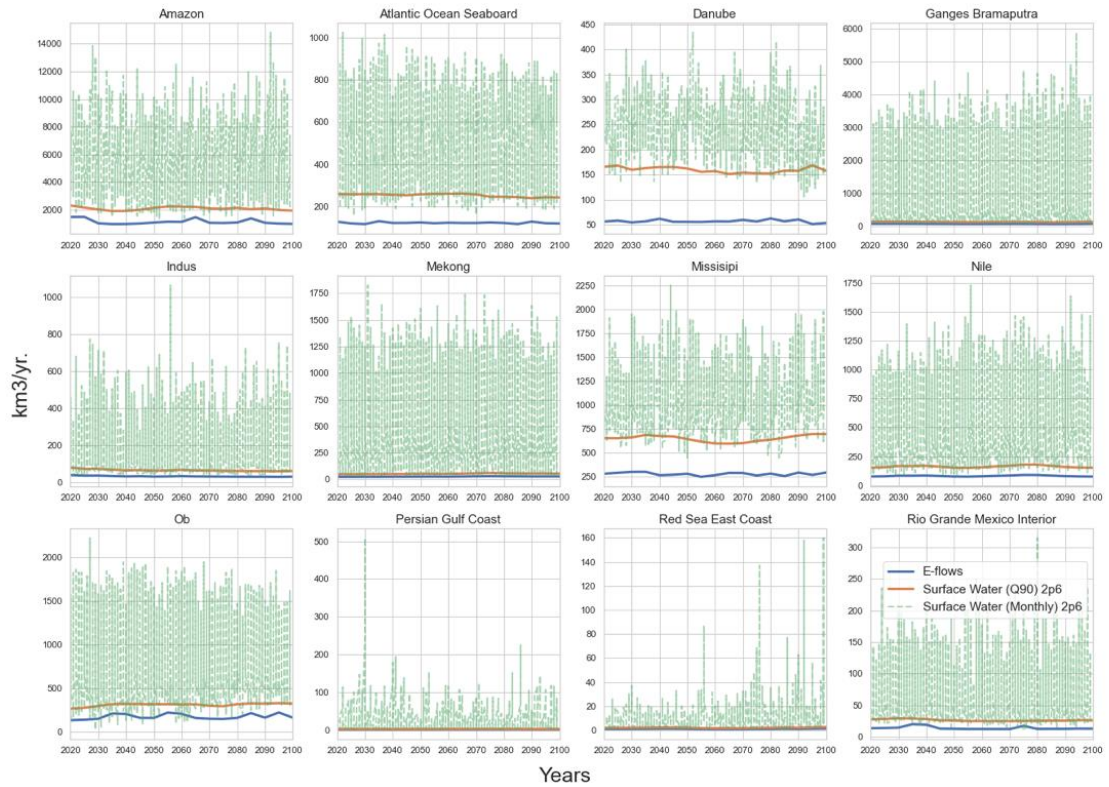


Figure B-S2.1.1 shows the hydrological data used within the nexus module for major B210 basins within the nexus module. Q90 flows which are used as a high reliability scenario, and environmental flows are overlaid on the monthly profiles of time-series to show the reliability of water across the season and over a long time horizon.

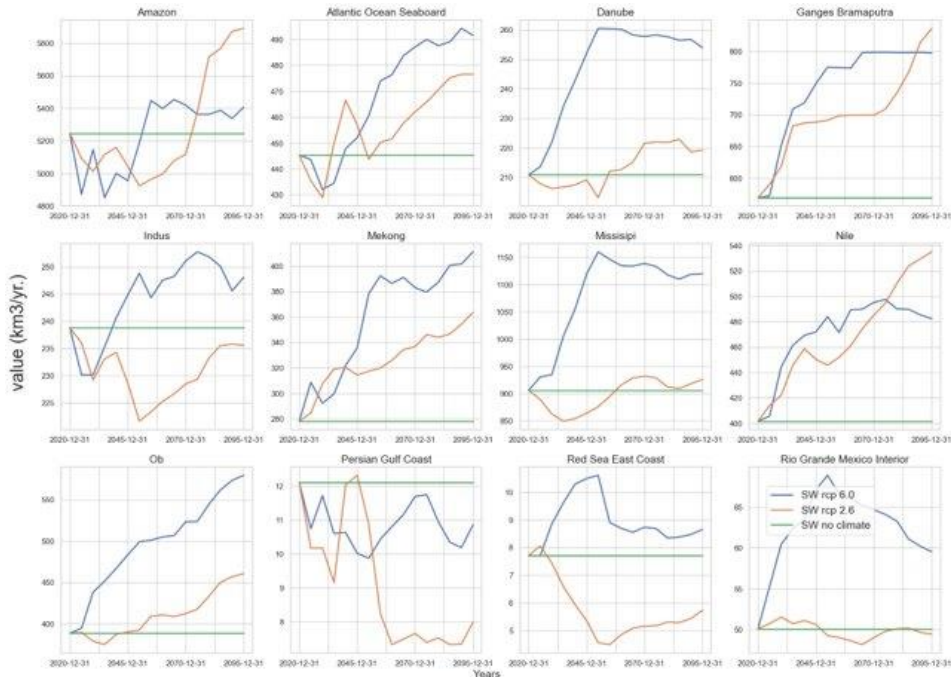


Figure B-S2.1.2: Hydrological flows for different climate scenarios for major B210 basins across timeseries

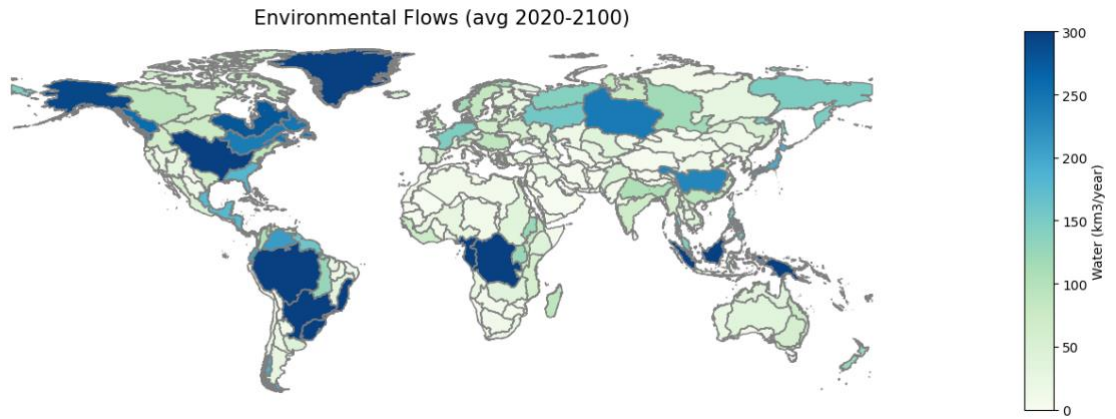


Figure B-S2.1.3 shows average (2020-2100) environmental flows within B210 basins



Figure B-S2.1.4 shows the reliability scenarios for the Zambian sub-regions. Per section 3.4 of the main paper, the global model is downscaled to Zambia on a similar structure.

S3 Exogenous Water Demands

S3.1 Municipal water demands

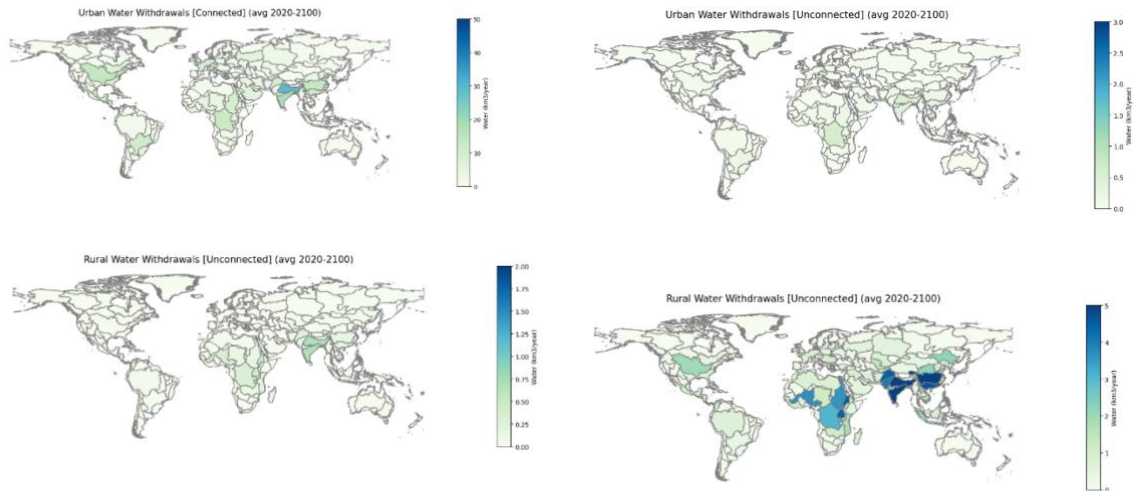


Figure B-S3.1.1 Average municipal withdrawals (Urban, Rural (Connected & Unconnected)) for B210 basins. The complete data is available in the GitHub repository under data/water/water_demands

S3.2 Industrial water demands

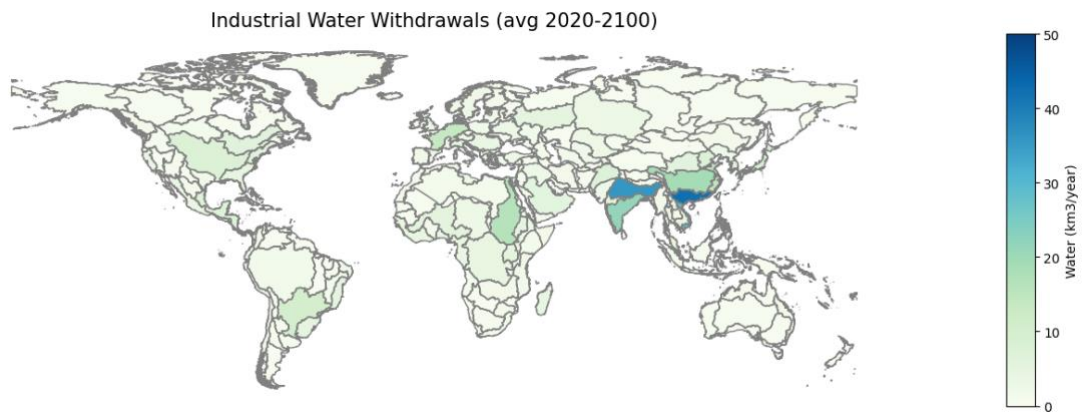


Figure B-S3.2 Average industrial water withdrawals

S3.3 Water Infrastructure

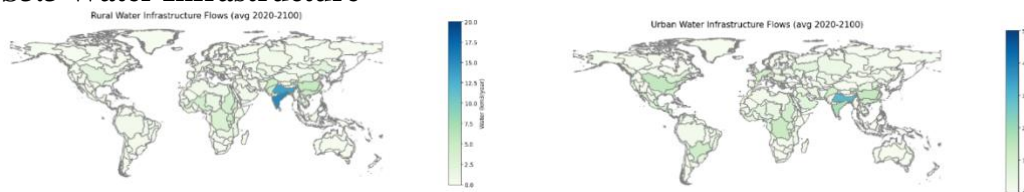


Figure B-S3.3 Average Urban & rural water transmission

S3.4 Recycled wastewater

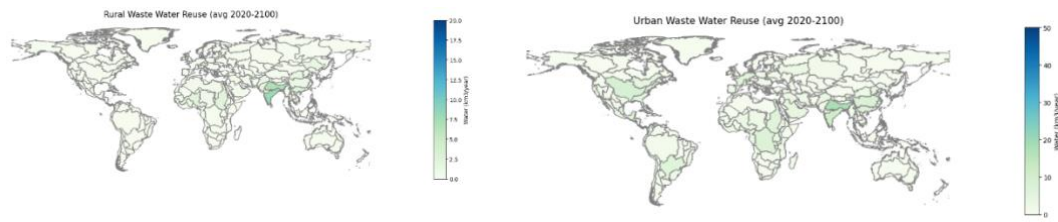


Figure B-S3.4 Average wastewater reuse available as additional supply in the supply system

S4 Biophysical Climate Impacts

S4.1 Water Sector

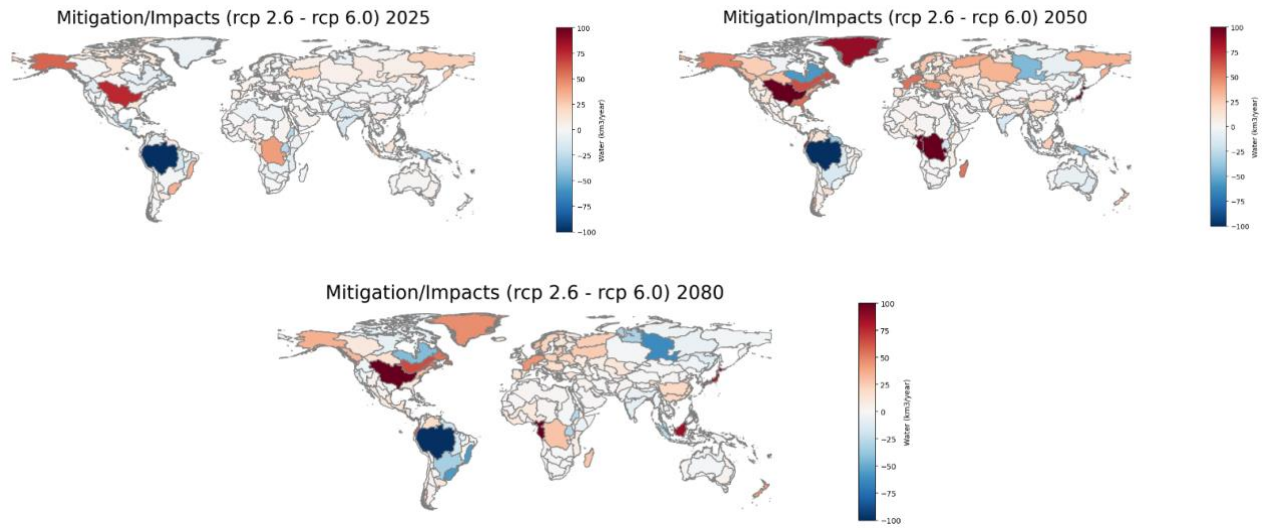


Figure B-S4.1.1 Water Resources (surface water & groundwater) variation between rcp 6 & rcp 2.6 scenarios

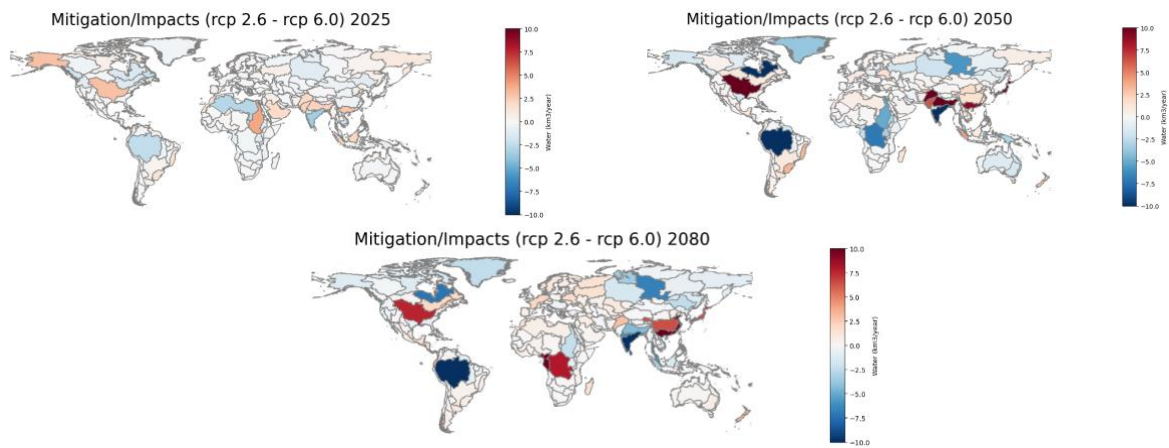


Figure B-S4.1.2 Water extraction (all sectors) variation between rcp 6 & rcp 2.6 scenarios

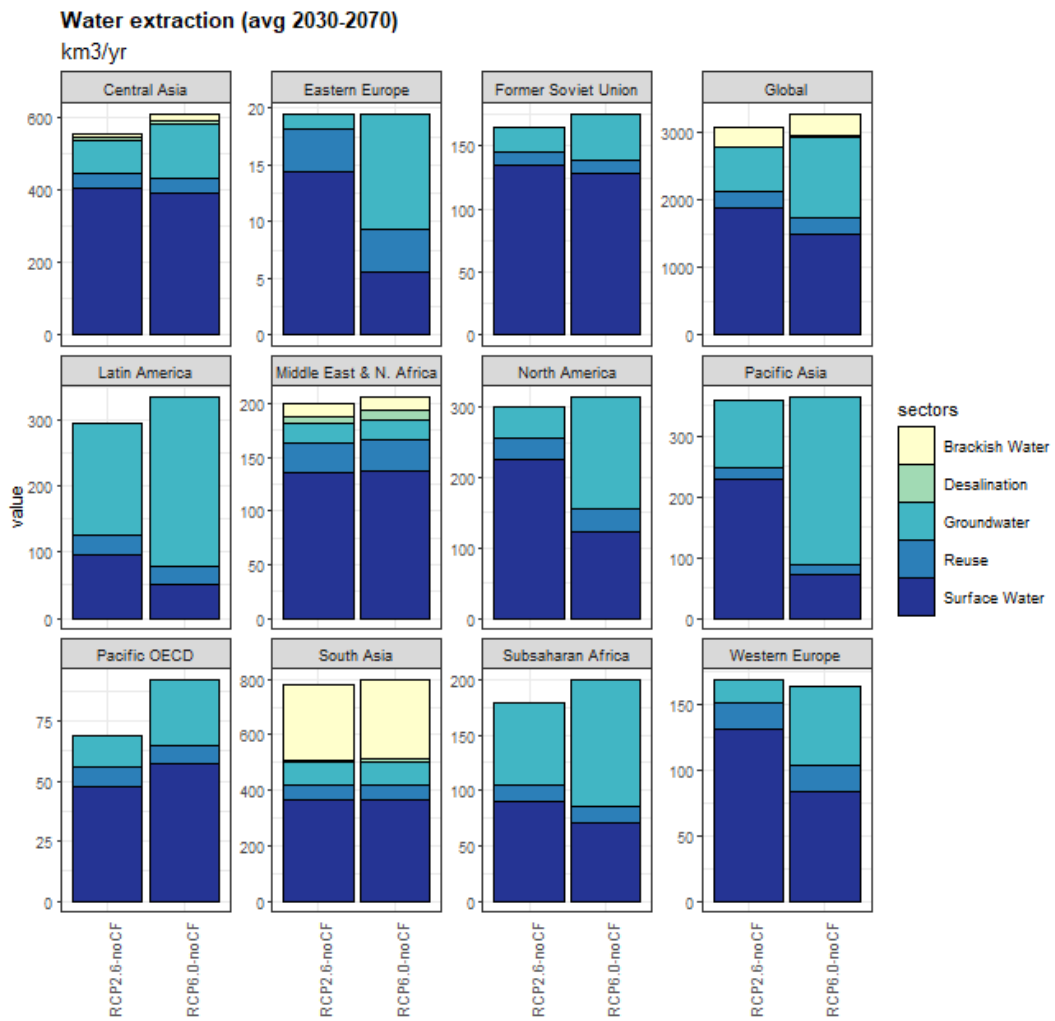


Figure B-S4.1.3 Water Extraction outlook for no climate feedback scenarios

Water Balance 2050

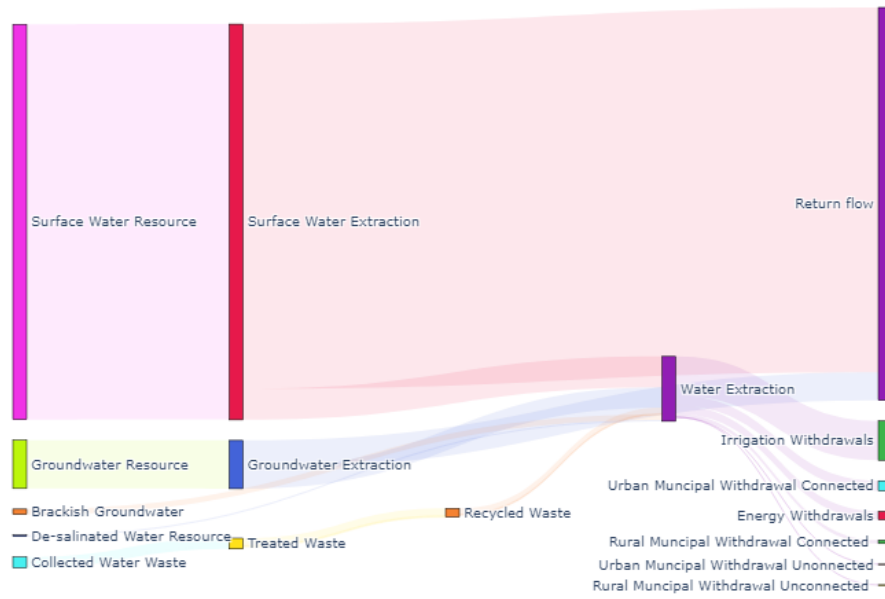


Figure B-S4.1.4 Water flows from supply to source in the water sector of the MESSAGEix-GLOBIOM nexus module. The flows and associated techno-economic parameters can be tracked as model outputs across the time horizon and scenarios.

S4.2 Energy Sector

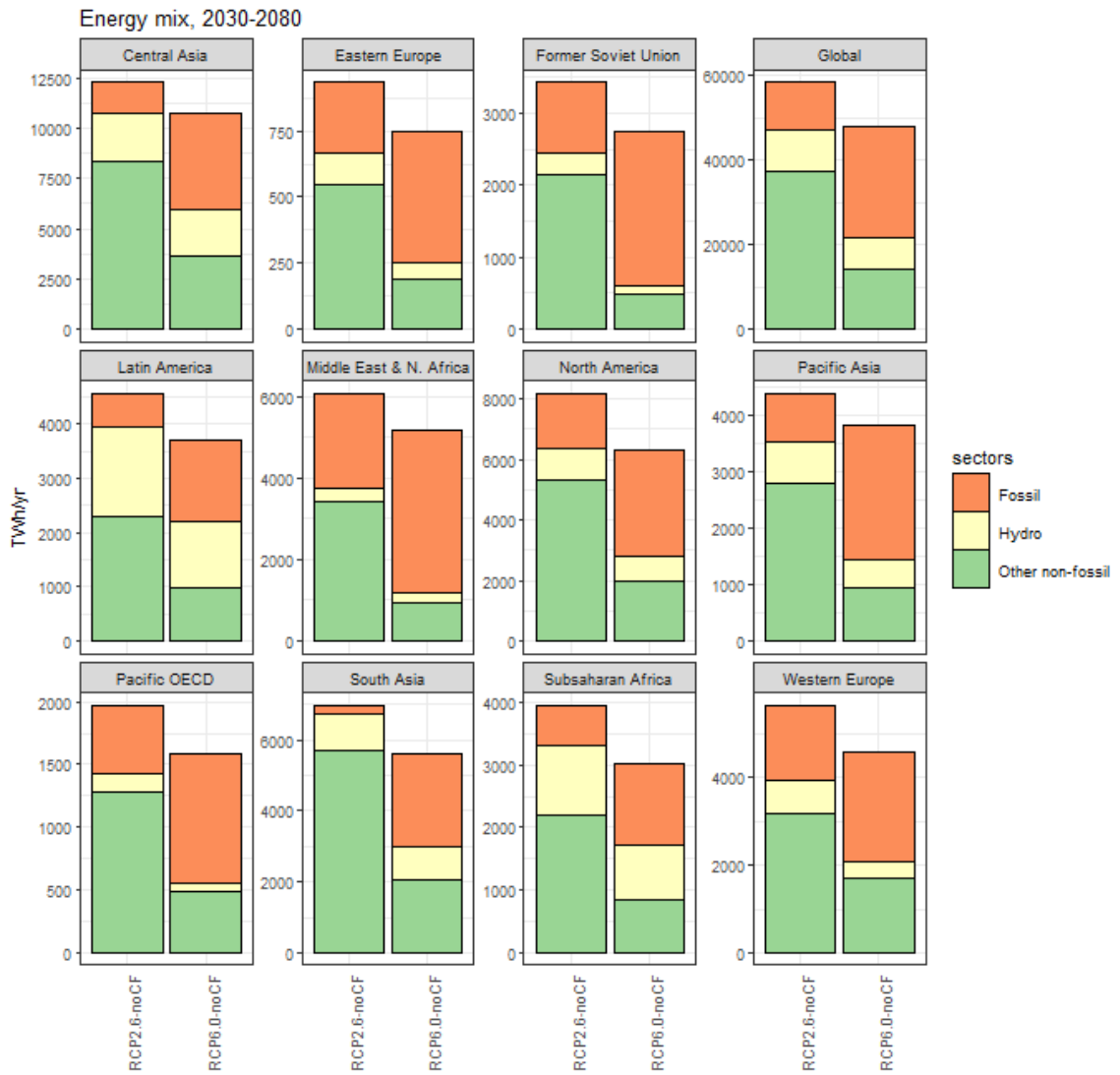


Figure B-S4.2.1 Energy Generation mix for no climate feedback scenarios

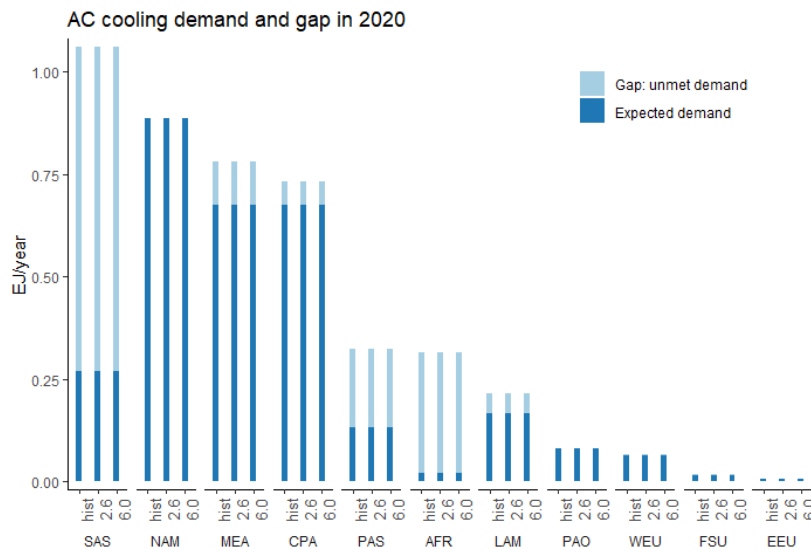
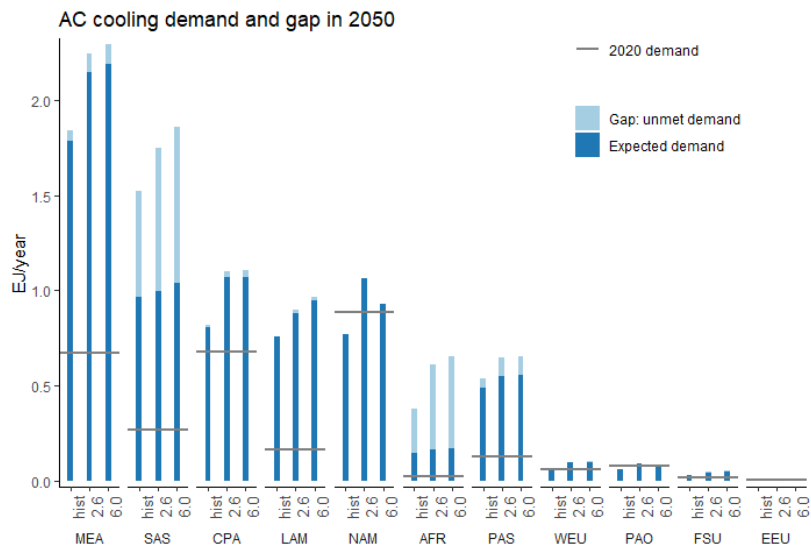


Figure B-S4.2.2 A/C cooling demand

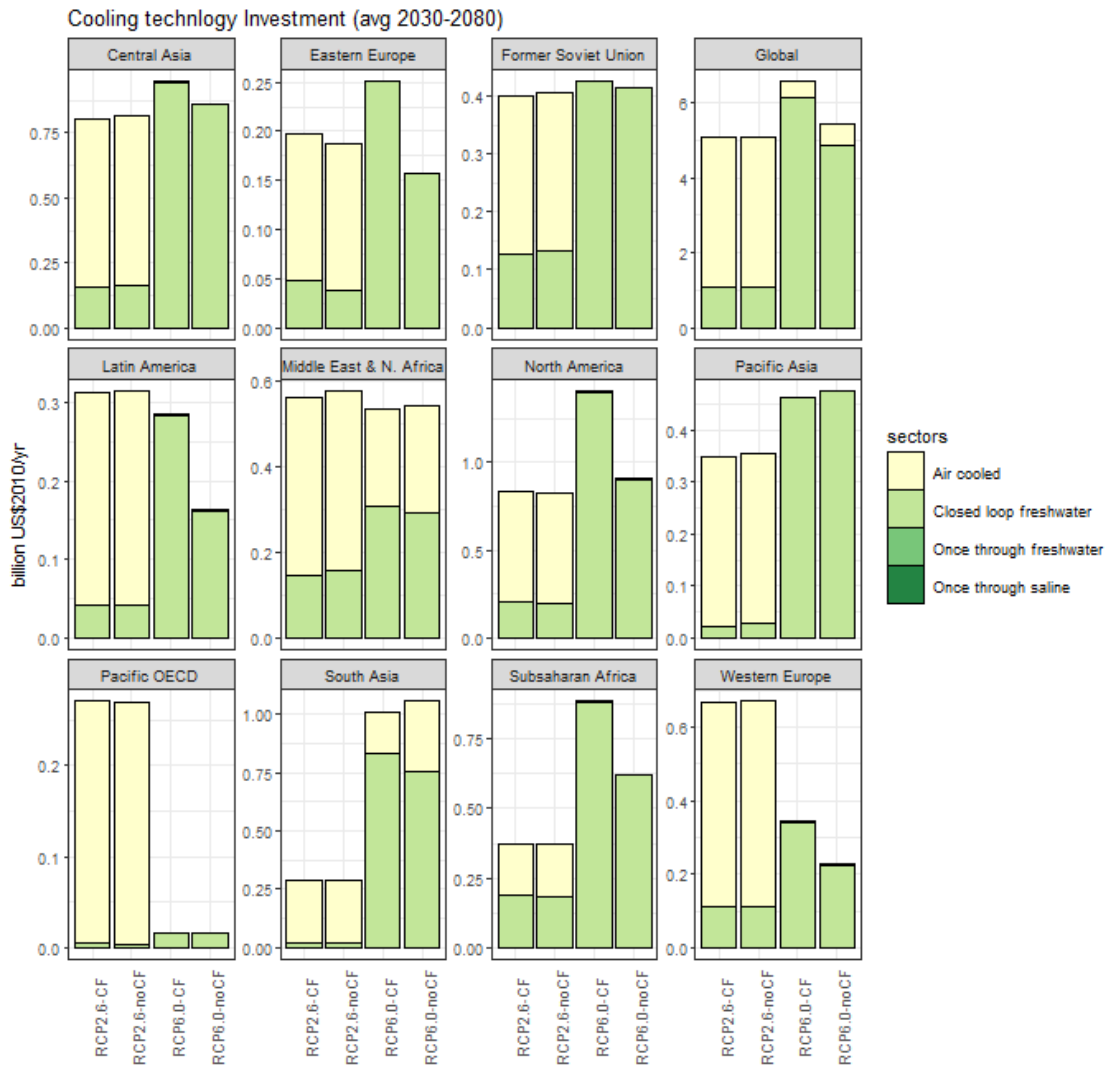


Figure B-S4.2.3 Climate impact on cooling water discharge

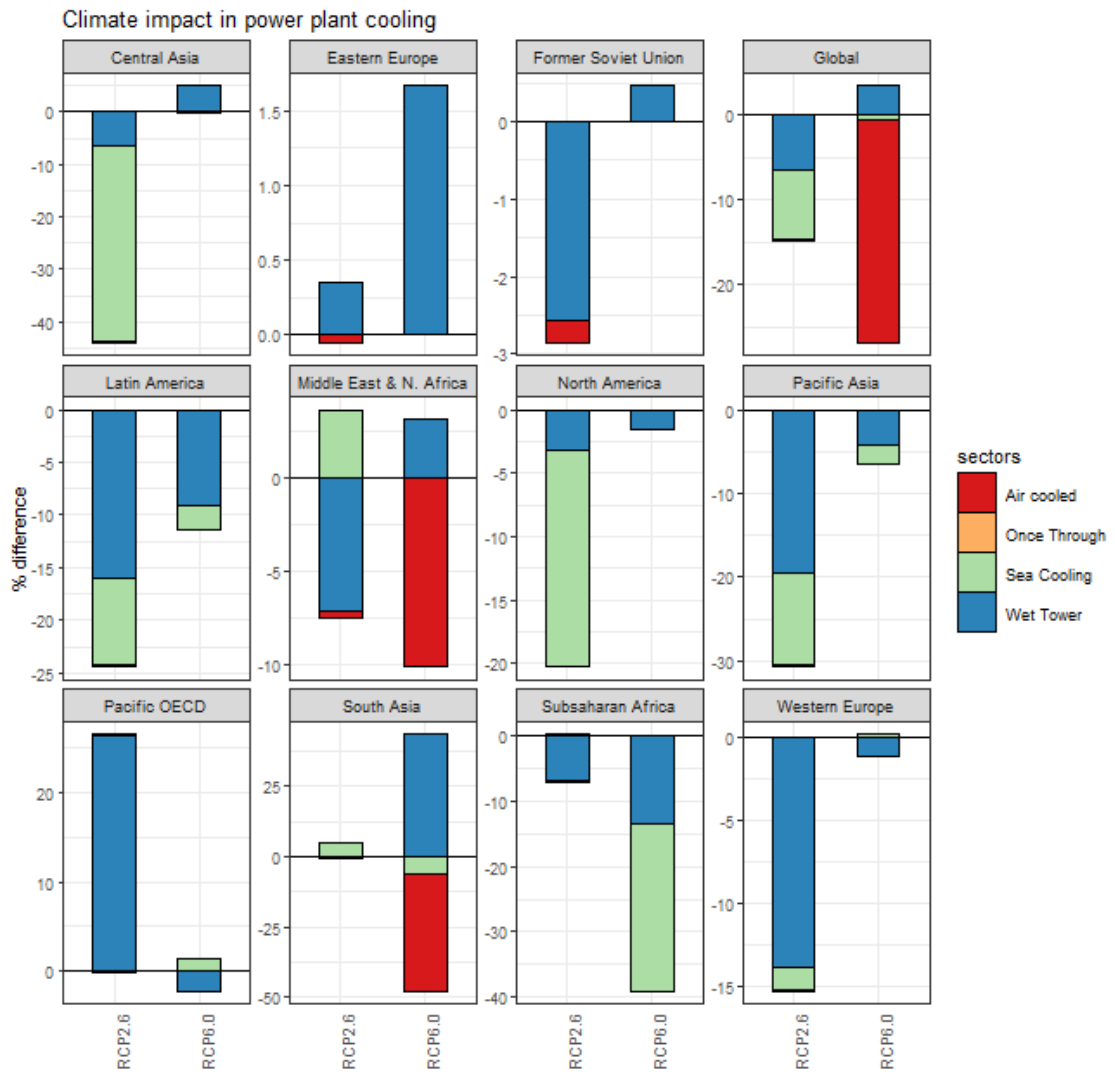


Figure B-S4.2.4 Percentage of investments of climate impacts on cooling water discharge

S5 Flexibility across scales

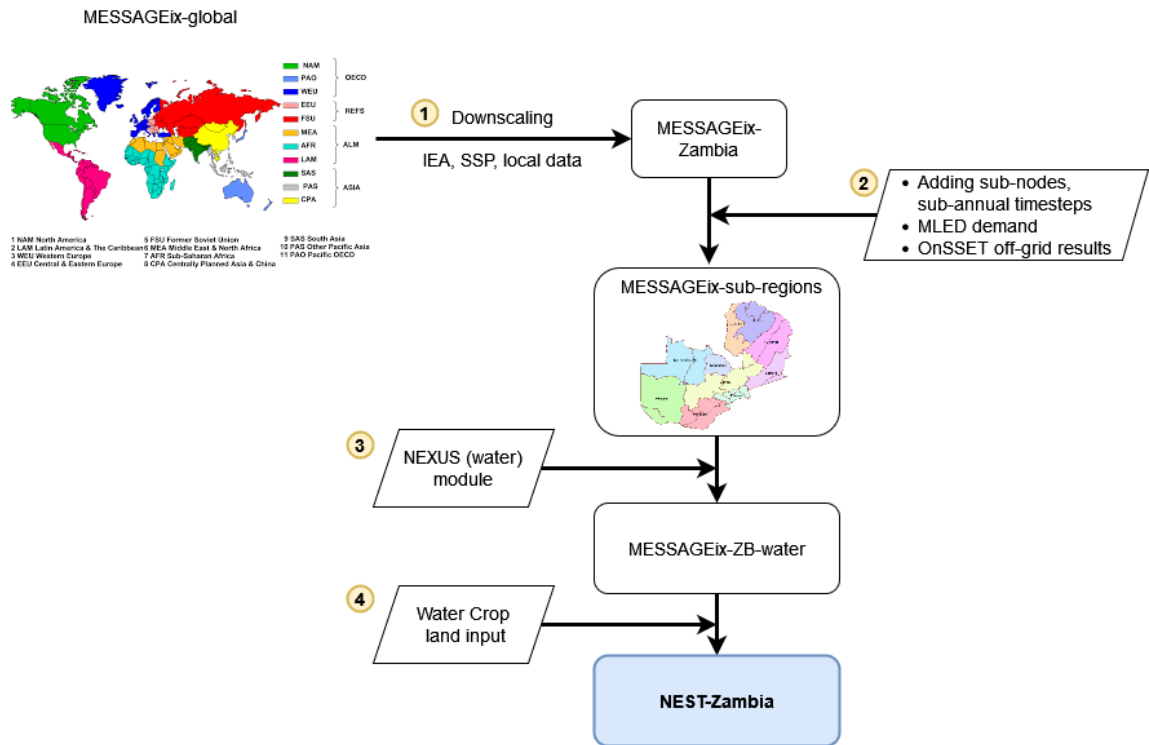


Figure B-S5 Downscaling global nexus module at national scale