MESSAGEix-GLOBIOM Nexus Module: Integrating water sector and climate impacts

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Abstract. The Integrated Assessment Model (IAM) MESSAGEix-GLOBIOM developed by IIASA is widely used to analyse 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 different sources, suggesting possible shifts in the energy and land sectors.

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 (Parkinson et al., 2018, 2019; Khan et al., 2017, 2018). In addition to climate change risks, limited resources compounded by population and GDP growth pose an additional challenge.~~Limited resources and increasing demands due to population and GDP growth pose an extra threat to climate change risks~~ (Byers et al., 2018). Integrated Assessment Models (IAMs) help researchers and policymakers understand the long-term consequences of varying 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 different 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 ~~global warming~~climate policy goals.

Substantial efforts have been made in developing scenarios informing a range of futures with varying societal and socioeconomic assumptions. (Riahi et al., 2017) The most commonly 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 Representation Concentration Pathways (RCPs), a set of four scenarios spanning a range of radiative forcing values (van Vuuren et al., 2011). These narratives have been translated into assumptions for economic growth, population change, and urbanization to analyse baseline and climate mitigation scenarios (Riahi et al., 2017b)(Riahi et al., 2017b)(Riahi et al., 2017b).

Although SSPs were designed to analyse 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 relatively limited in the IAM scenarios (Riahi et al., 2017) 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., 2021a).~~Scenarios often neglects the climate impacts on system performance, resulting in avoiding adaptation costs in the analysis~~ (Calvin et al., 2013; Piontek et al., 2021a)~~.~~ Many IAMs often consider ~~adaptation –~~ = costs of resources in an aggregated spatial region/continent. In the case of an adaptation, the key element for change ~~could be~~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 carried out 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. 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. 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. (Piontek et al., 2021b) analyzed the economic impacts of climate change using the REMIND IAM model, but biophysical climate impacts were not represented.(Soergel et al., 2021a, b) emphasized the significance of considering the consequences of climate impacts and evaluating how integrated scenarios respond to these impacts, especially regarding sustainable development pathways. 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.

New analytical approaches and solutions are required to address the challenges of impact and adaptation in long-term policy analysis (Wang et al., 2016; Patt et al., 2010; Riahi et al., 2017). By introducing climate impacts in the development trajectories, such as the SSP framework, the regional inequality of climate impacts' exposure can also be considered (Taconet et al., 2020). There is a need for a balanced ~~integration~~ 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, simultaneously, meeting growing population-driven demands in the EWL sectors (Rasul and Sharma, 2016). ~~Cross-sectoral nexus analysis integration in IAMs can help identify trade-offs and synergies and integrate policy implementations. It can also help address poverty and vulnerability linkages to increase communities' resilience.~~ The integration of 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.

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 (Parkinson et al., 2019; Fricko et al., 2016). 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 ~~describes~~ introduces a new~~the nexus~~ module of the global ~~IAM~~ MESSAGEix-GLOBIOM framework (Riahi et al., 2021; Krey et al., 2016). 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. Using this module, we develop scenarios that can effectively capture climate impacts across

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multiple sectors. 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. ~~endogenizing water allocation decisions and linking water, energy, and land (WEL) climate impacts as well as important SDG targets across sectors.~~

~~The module here refers to extending 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. 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 numerous policy objectives, such as reducing greenhouse gas emissions, boosting food security, and safeguarding natural resources. In order to access sustainable development targets, the framework is utilized to evaluate the feasibility and implications of alternative policy choices and to guide decision-making. For instance, it can be used to analyse the potential effects of changing to a low-carbon economy on food production and land usage and the feasibility of attaining global climate targets while preserving food security.~~

~~One of the key advantages of the MESSAGEix-GLOBIOM framework is its ability to simulate global interactions across many sectors and systems. It allows the model to represent the complex feedback and spill over effects from policy interventions, such as the potential implications of land use changes on the global food system and the energy sector. 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. In the context of sustainable development, it can analyse the viability and implications of various policy alternatives and inform decision-making.~~

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 ~~adaptation~~ flexibility at ~~several~~ 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.

2. Model structure & workflows

Least-cost optimization using engineering-economic modelling 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 analysing sustainable transition in climate change mitigation and sustainable socioeconomic development (Khan et al., 2018; Huppmann et al., 2019). Engineering-economic modelling methods to quantify impacts and ~~adaptation~~ 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 modelling 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.

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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 carried out by (Parkinson et al., 2019) 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 a 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 numerous 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~~It~~ 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 several sources, such as surface water, groundwater, and desalinated water.

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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 ~~optimization problem~~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.

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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.

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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.

Further information on the typical scenarios of MESSAGEix-GLOBIOM can be found in (Krey et al., 2016) The scenario is further extended from the typical scenario in the nexus module using ~~a set of configurations in the energy systems~~certain policy and technological assumptions. The configuration can handle any SSP-RCP combinations to allow accessing a diverse range of pathways compared to each other and the Reference scenario.

3 Water, Climate, and SDG implementation and results

The subsequent sections explain the modelling 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

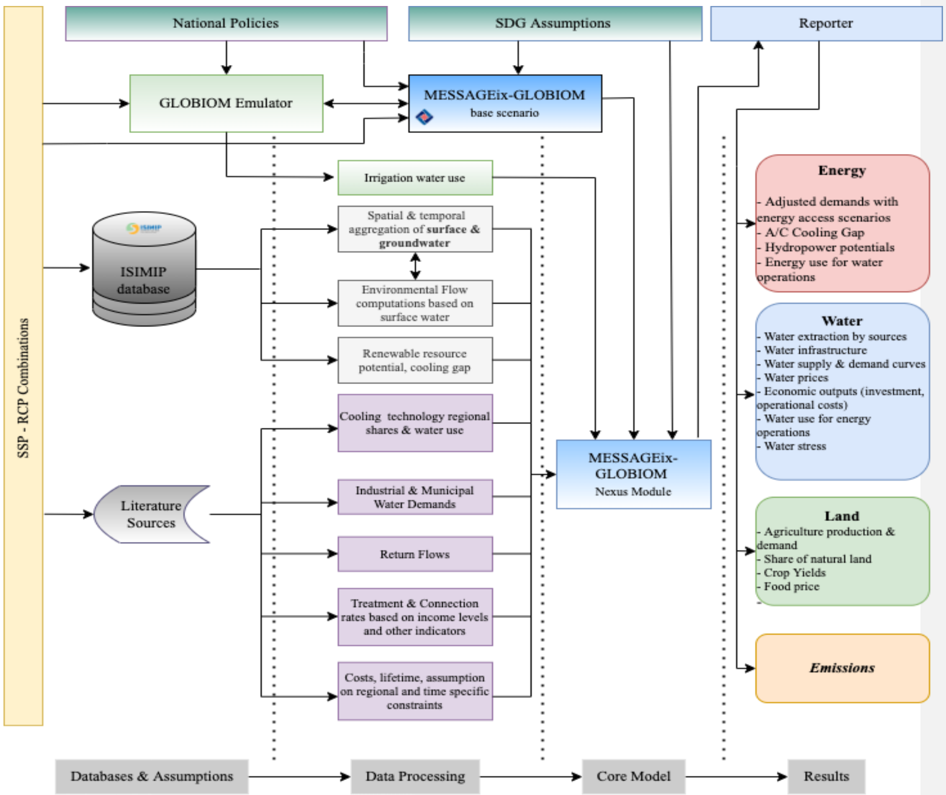

Figure 1 Structure & data flows of MESSAGEix-GLOBIOM Nexus Module. SSP-RCP combinations of scenarios are used as basis for development of nexus module. The module is built on the typical MESSAGEix-GLOBIOM scenario. The typical scenario has updated biophysical climate impacts in the energy and land sectors and then the water system is ~~model~~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.

3.1 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 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 HydroShed 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 2), providing a more powerful depiction of the supply-demand system (Figure 2). The energy demand for water uses and water withdrawals for irrigation and~~,~~ ~~energy, and~~ thermal power plant cooling are 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 the fact 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. The usage of 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 ~~pathways~~needs~~t~~. 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.

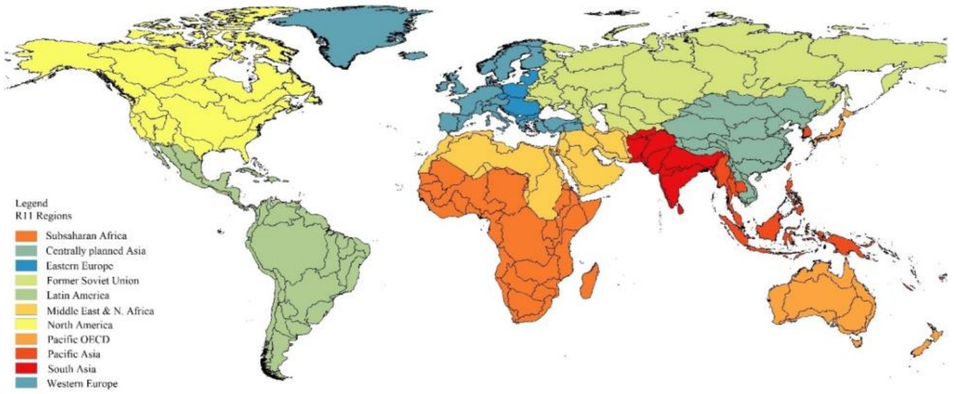

Figure 2 Delineation of basins within the MESSAGE R11 regions. The HydroSHEDs basin level 3 is intersected with MESSAGE R11 regional delineation, and the new polygon are used as decision units in the water sector. The distinct colors in the maps represent R11 regions however polygons inside each distinct 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)

The water balance in the water sector of the IAM is

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

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

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., 2014) *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 (Palazzo et al., 2019; Frank et al., 2021). 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)(Burek et al., 2019) and GHM outputs from ISIMIP (Frieler et al., 2017b).(Frieler et al., 2017b). 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.

~~.~~For temporal aggregation, we apply a quantile approach with monthly freshwater (surface and groundwater) resources 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 what is considered 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 (Prudhomme et al., 2014; Satoh et al., 2022; Gleeson and Richter, 2018) 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 overlayed on the monthly flow data for the significant basins to show their reliable flows. We have run the scenarios for testing the model's sensitivity based on the flow quantiles.

For calculating the municipal water demands, we used the approach followed by (Graham et al., 2020). Urban and rural components of municipal water demand projections are calculated using gridded population and income-level projections data by (Wang and 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.

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The wastewater treatment system is adapted and improved from the previous implementation by (Parkinson et al., 2019) Figure 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

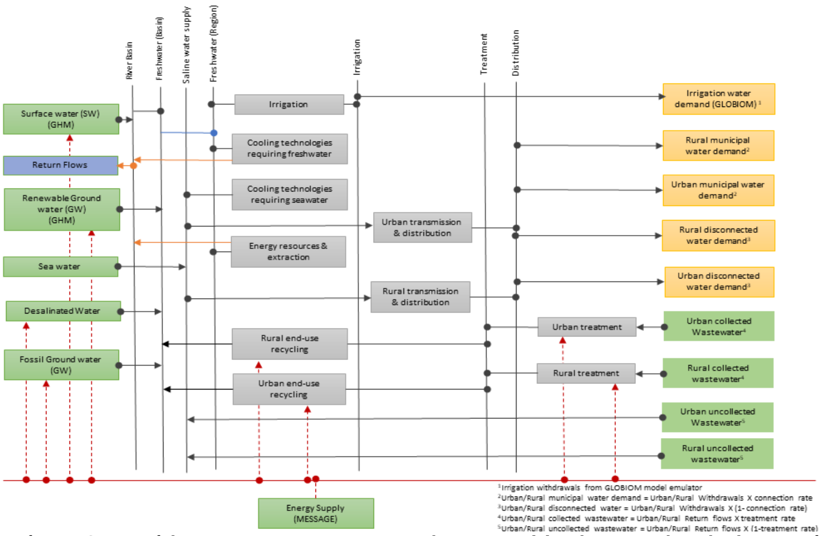

Figure 3: Reference System of the water system representation in the nexus module. The arrows show the direction of input/output of different technologies within the framework. Energy footprint of water system is tracked at different supply steps and infrastructure technologies.

desalination potentials have been estimated following the approach in (Parkinson et al., 2019), 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).

For calculating water withdrawal and return flows from energy technologies, we use the approach detailed by (Fricko et al., 2016). Each energy technology requiring water is provided with a withdrawal and consumption intensity (e.g., cubic kilometers per GWh), which then allows the model to translate technology outputs into water requirements and return flows, which in turn 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 in (Fricko et al., 2016).

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 1 indicated different references used for electricity requirements per unit of water infrastructure activity at different stages.

Table 1: Data sources used for various parameters and input variables

Parameter	Description	Data
Basin boundaries	Basin boundaries used from the HydroSheds database (Lehner et al., 2006)(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 use and investments (Meldrum et al., 2013b)(Meldrum et al., 2013b) are updated based on the latest powerplant database from Platts (Platts Market Data – Electric Power | S&P Global Commodity Insights, 2022)	All the processed files are available in the GitHub repository in CSV format(~data/water/ppl_cooling_tech)
	Hydropower use and investments (Grubert, 2016)	
	Parasitic electricity requirements (Dai et al., 2016)	
	Regional shares of cooling (Raptis et al., 2016)	
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.	All the processed files are available in the GitHub repository in CSV format (~data/water/water_availability)
	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	

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	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 et al., 2020) and (Liu et al., 2016).	The energy consumption values vary regionally based on the groundwater table depths. Thus, the processed file is 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 et al., 2020) 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.	All the processed files are available in the GitHub repository in CSV format (~data/water/water_demands)
	Irrigation water demands are used from the GLOBIOM model for a set of scenarios aimed to achieve multiple, different SDG goals (Frank et al., 2021)	GLOBIOM Emulator
	Treatment & access rates are re-calculated using the approach described in (Parkinson et al., 2019) 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)
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_infrastructure)
	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., 2020), 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.	

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. For considering the climate impacts, we use the data for RCP2.6 and RCP6.0, i.e., emission pathways reaching 2.6 W/m^2 and 6.0 W/m^2

forcing levels in 2100. We have not included GDP and labour productivity implications to focus solely on biophysical impacts.

Table 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 (Mastrucci et al., 2021; Byers et al., 2018) 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, which are accordingly mapped to the crops in GLOBIOM following (Müller and 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., 2020)
Desalination potential	Desalination potential climate impacts are based on water stress outputs from the combinations of GHMs & GCMs from (Byers et al., 2018)

The climate impacts on hydropower energy supply have been based on (Gernaat et al., 2021) ~~(see Figure 2 for a schematic overview of the approach)~~. 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, 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) have presented relatively small impacts on renewable energy supply.

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, summarised 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 level to the MESSAGE region level. 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) is used to model 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 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 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 and Pachauri, 2018; Poblete-Cazenave et al., 2021) 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 (Poblete-Cazenave and Pachauri, 2021; Pachauri et al., 2021). An estimation model takes as input micro-level data from nationally representative household surveys covering different regions of the world to estimate behavioural 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., 2014) to constrain the monthly surface water available for human use based on environmental flow requirements (EFRs) for wet and dry seasons. ~~We use the Variable Monthly Flow (VFM) method~~ (Pastor et al., 2014) ~~to constrain the monthly surface water available for human use based on environmental flow requirements (EFRs) for wet and dry seasons.~~ 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 increasing 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

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Formatted: Font: (Default) Times New Roman, 10 pt, Not Bold, Font color: Auto 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 a minimum of 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 (Parkinson et al., 2019).

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., 2021). (Pastor et al., 2019) 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 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).

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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.

Table 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 - Decrease animal calorie intake to 430 kcal/capita/day by 2030 from current levels in overconsuming countries (USDA recommendations for healthy diets)	- Food production - 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., 2021)	- Water withdrawal (irrigation)
	-	Based on the variable monthly flow (VMF) method developed by (Pastor et al., 2014) 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., 2021) 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

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 tested 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., 2022) discusses the application of such linkages and further details.

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 4 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 analysing 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 set of scenario ~~formulation~~ combination is possible from the module, but to test the model's applicability across climate and SDG scenarios in combination, we formulated a total of six scenarios that alternate different assumptions. For the current setup we used combination SSP2 pathways combined with RCP2.6 & RCP6.0. The upcoming work will include more SSP dimensions in combinations with RCPs to have more consistent assumptions across scenarios. ~~on three dimensions: climate mitigation target, climate impacts and SDG policy implementation (Table 4)~~.

The scenario formulation we used to describe results are 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

~~**Table 4**: Scenario formulation of the nexus module.~~

~~**Scenario name**~~	~~**Emissions pathway consistent with (W/m2)**~~	~~**Climate impacts**~~	~~**SDGs**~~
~~SSP2-noCF~~	~~RCP6.0~~	~~No~~	~~No additional effort~~
~~SSP2-CF~~	~~RCP 6.0~~	~~Yes - RCP 6.0~~	~~No additional effort~~
~~SSP2-26-noCF~~	~~RCP 2.6~~	~~No~~	~~No additional effort~~
~~SSP2-26-CF~~	~~RCP 2.6~~	~~Yes - RCP 2.6~~	~~No additional effort~~
~~SSP2-SDG-noCF~~	~~RCP 6.0 (frozen to 2020)~~	~~No~~	~~SDG 2, 6, 7,15~~
~~SSP2-SDG-CF~~	~~RCP 6.0~~	~~Yes - RCP 6.0~~	~~SDG 2, 6, 7,15~~
SSP2-26-SDG-CF	RCP 2.6	Yes - RCP 2.6	SDG 2, 6, 7, 13 ,15

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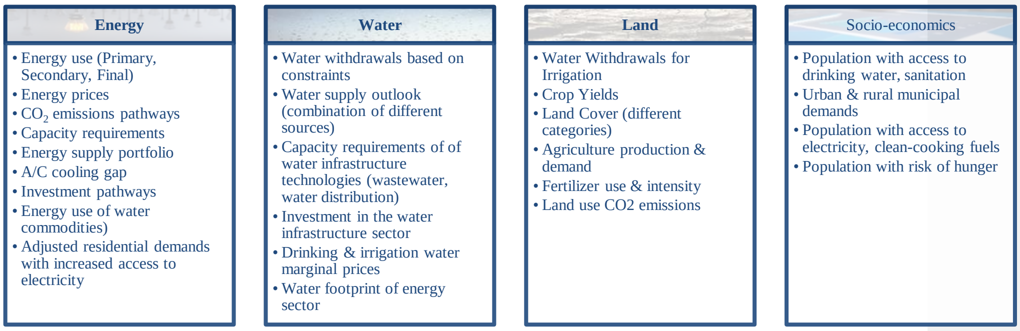

Figure 4: Summary of output indicators that are possible from the MESSAGEix-GLOBIOM nexus module. These outputs are long term pathways and much of these outputs can be further disaggregated onto the technology level.

~~In the MESSAGEix-nexus module, we distinguish between rural and urban water demands, allowing us to produce additional useful outputs (Supplementary Section S3 visualizes different demands). For example, the energy footprints of water systems from source to demand could provide valuable insights into climate and sustainable development policies across spatial-temporal dimensions. Additionally, the conjunction of environmental flow limits with water extraction for sectoral demands is another possible dimension of the results that could inform resource management decisions. When combined with socioeconomic indicators such as population and GDP, these results can provide further information on the climate resilience and adaptation of integrated resource systems. These outputs will be explored in the upcoming publications and are beyond the scope of this paper.~~

~~In our study, we ran three reliability scenarios based on the flow reliability of Q90 (High Reliability), Q70 (Medium Reliability), and Q50 (Low Reliability) to test the sensitivity of these assumptions on the results. These scenarios were designed to evaluate the amount of available renewable water that is reliable throughout the year, as infrastructure is often designed to be robust under minimum flow conditions. We found that as reliability increases from low to medium, the additional investment in alternative water sources such as fossil groundwater, desalination, and other high-cost solutions increases globally by approx. 35.5 billion USD/yr. (Figure 5). Similarly, when the system adopts a high-reliability flow, an additional investment of 57 billion USD/yr. is required for alternative water sources. Additionally, we observed a significant increase in water infrastructure costs as reliability decreased. Moving from low to medium reliability requires an additional investment of 38 billion USD/yr. in water infrastructure, including costs for wastewater treatment and recycling facilities and operational and management expenses. An investment of 44 billion USD/yr. (Figure 5). is required to move from low to high reliability. Regional differences were also noted, with exceptionally high costs observed in South Asia, the Middle East, and North African basins, where much of the cost is associated with alternative water sources and infrastructure.~~

To ~~test~~ understand the biophysical effects of climate change on multiple sectors~~. To do this~~, we ~~developed~~ 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). ~~two climate scenarios, one based on RCP 2.6 and the other on RCP 6.0, respectively (SSP2-26-CF). To assess the outcomes of the climate scenarios, we also developed a no-climate scenario (SSP2-noCF and SSP2-26-noCF)~~. Despite being physically impractical, the ~~no-climate~~Reference scenario aids in our comprehension of the results of biophysical consequences by projecting historical climate data into the future. The model incorporates the biophysical consequences, highlighting various potential outcomes in numerous ~~industries~~sectors.

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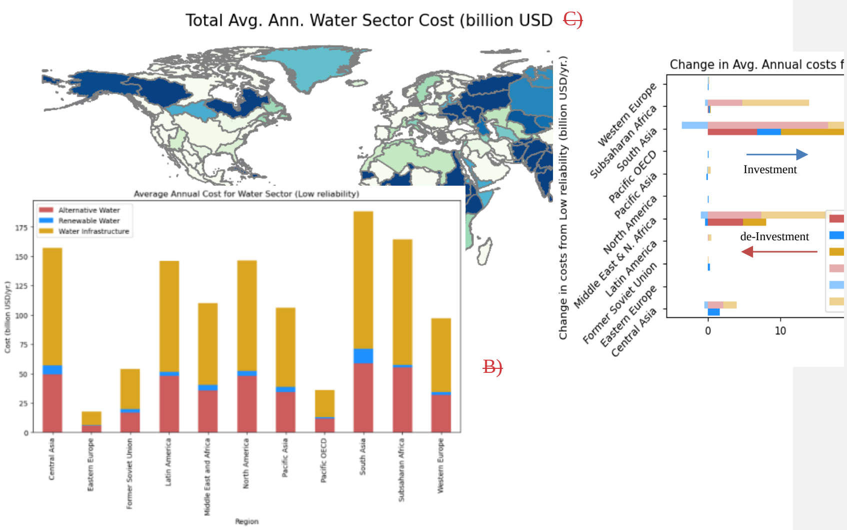

~~**Figure 5** Investments & operational aggregated costs across the water sector and averaged across the time horizon (2020-2100) Costs are in billion USD/yr. **A)** Spatial variation of the total water sector costs. B) Sectorial cost variation in the Low reliability scenario C) Change in average annual costs from the low-reliability scenario to see how the sectoral outlook changes when the water system changes from low to medium and low to high reliability.~~

~~Climate change has a noticeable impact on the mix of power generation and how we generate and consume energy. The effects of climate change on thermal power plant cooling water discharges are one of the contributory factors to this effect. As temperatures increase, the efficiency of thermal power plants decreases, and more cooling water is required to sustain their operation, which can result in decreased water availability and more significant expenditures. Changes in hydropower potential can also impact the mix of energy generation. As climate change alters precipitation patterns and water flow, it can impact the quantity of hydropower that can be~~

~~generated. Here, we estimate the electrical production mix, showing the diversification of the fossil, hydropower, and non-fossil sectors, including solar, hydro, biomass, and nuclear. When climate impacts are incorporated into the model for the mitigation scenario (RCP2.6 in Figure 6A), the findings indicate an increase of roughly 1,500 TWh/yr. in non-fossil and hydro in the energy mix and a drop of approximately 500 TWh/yr. in fossil in the energy mix. This transition from fossil technologies to renewables is also apparent in the RCP 6.0 scenario. The analysis also shows that regions such as Western Europe, the Pacific OECD, and North America have a reduction of around 100 TWh/yr. in the proportion of fossil fuels in the energy mix. Supplementary Figure S4.2.1 shows the baseline energy mix outputs.~~

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 provide 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 range of 3365–3656 km3/yr., echoing figures found in established literature (refer to Table X for a comparison). An important constituent of water management, global wastewater collection, was quantified as an exogenous input in our model at approximately 310.22 km3/yr. for 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 figure of 186.6 km3/yr. and reported by (Jones et al., 2021). The study also scrutinized agricultural withdrawals, an essential sector of water use. For 2020, our model computed this at 2666.36 km3/yr., a figure between the 1250–2000 km3/yr. range. Reported by (Burek et al., 2020) and closely matching the 2735 km3/yr. posited by (Sutanudjaja et al., 2018). Figure 5 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 flows 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 resources' availability as well as the associated operational and investment costs. The characterization of 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.

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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 have a direct impact on 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.

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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 Stefan et al. (cite). 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,

Formatted: Indent: Left: 2.54 cm, Line spacing: 1.5 lines pursuing the SDGs can result in a significant price increase due to increased allocation to environmental flows.

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.

~~Water extraction in the model is motivated by the withdrawals in different sectors, with a significant share of withdrawal from irrigation withdrawals assessed by the GLOBIOM model. Figure 6 B depicts the influence of climate impacts on water supply and withdrawals. Supplementary Figure S4.1.3 shows the water extraction in a no-climate impact scenario (SSP2-no-CF). Based on the results, renewable surface water and groundwater are limited and vary across different climatic scenarios. In particular, the impacts of climate change on crop yields have implications on irrigation withdrawals. The results also indicate a rise in the usage of brackish water, wastewater, and desalination in certain regions. These also indicate that renewable water resources are limited in these places. The study indicated that the global effects of climate impacts on the water sector depend on various locations' geophysical characteristics and land use effects. Some locations might experience favourable benefits, but others could suffer negative consequences. Depending on the region, the study discovered that climate impacts have beneficial and adverse effects on the water sector.~~

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~~Climate change may affect water availability in several ways depending on the region and hydrological factors. In certain regions, climate change may increase surface and groundwater availability, while in others, it may decrease water availability (Supplementary Section S2). Changes in precipitation patterns are a possible mechanism via which climate change might enhance water availability. In regions where water resources are low, an increase in precipitation may result in a more significant recharge of surface and groundwater, which can enhance water availability. Changes in temperature and evaporation rate may also increase the amount of water available for extraction in locations where surface water is sparse, and groundwater resources are rich. However, it is crucial to emphasize that these potential increases in water availability primarily rely on geophysical characteristics such as terrain, soil, vegetation, and water management. In many regions, the impacts of climate change on water availability are likely to~~

~~be negative, with changes in precipitation patterns causing droughts and floods, increased evaporation reducing streamflow and groundwater recharge, and increased frequency and severity of extreme weather events reducing water availability.~~

~~In addition, an increase in water availability does not always imply that it will be available for human and ecological use since it may be situated in distant or inaccessible regions. Moreover, water supply changes may result in water quality alterations, which can substantially affect human health and the environment. When considering the possible effects of climate change on water supply, it is thus essential to adopt a comprehensive approach. The sensitivity of yields to temperature and CO2 fluctuations, as well as the influence of water usage efficiency, is visible in the yield responses from the EPIC model. The effect of CO2 on crop yields is often more significant for sugar crops than other major crops. The positive effect of CO2 on water use efficiency can counteract or even reverse the negative impact of climate change on agricultural yields. The net yield effect is also influenced by fertilization intensity, and enhanced water usage efficiency would affect irrigation water requirements. In addition, the results should be interpreted with care because the study does not account for cultivar optimization.~~

Table 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)

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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.

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 (van Soest et al., 2019; Baumstark et al., 2021; Vuuren et al., 2022; Soergel et al., 2021a), 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 7). Although many IAMs scenarios already include the SDG dimensions, the innovation in this module combines SDG scenarios with climate impact scenarios. This type of scenario will be used in the upcoming studies to assess the benefits of mitigation and adaptation while also ensuring meeting sustainable development targets.

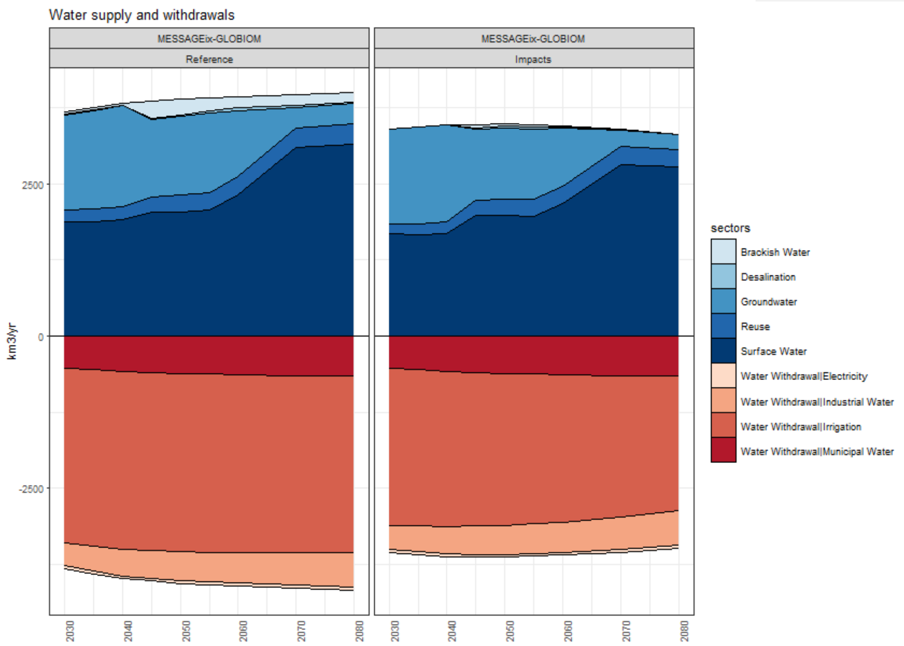
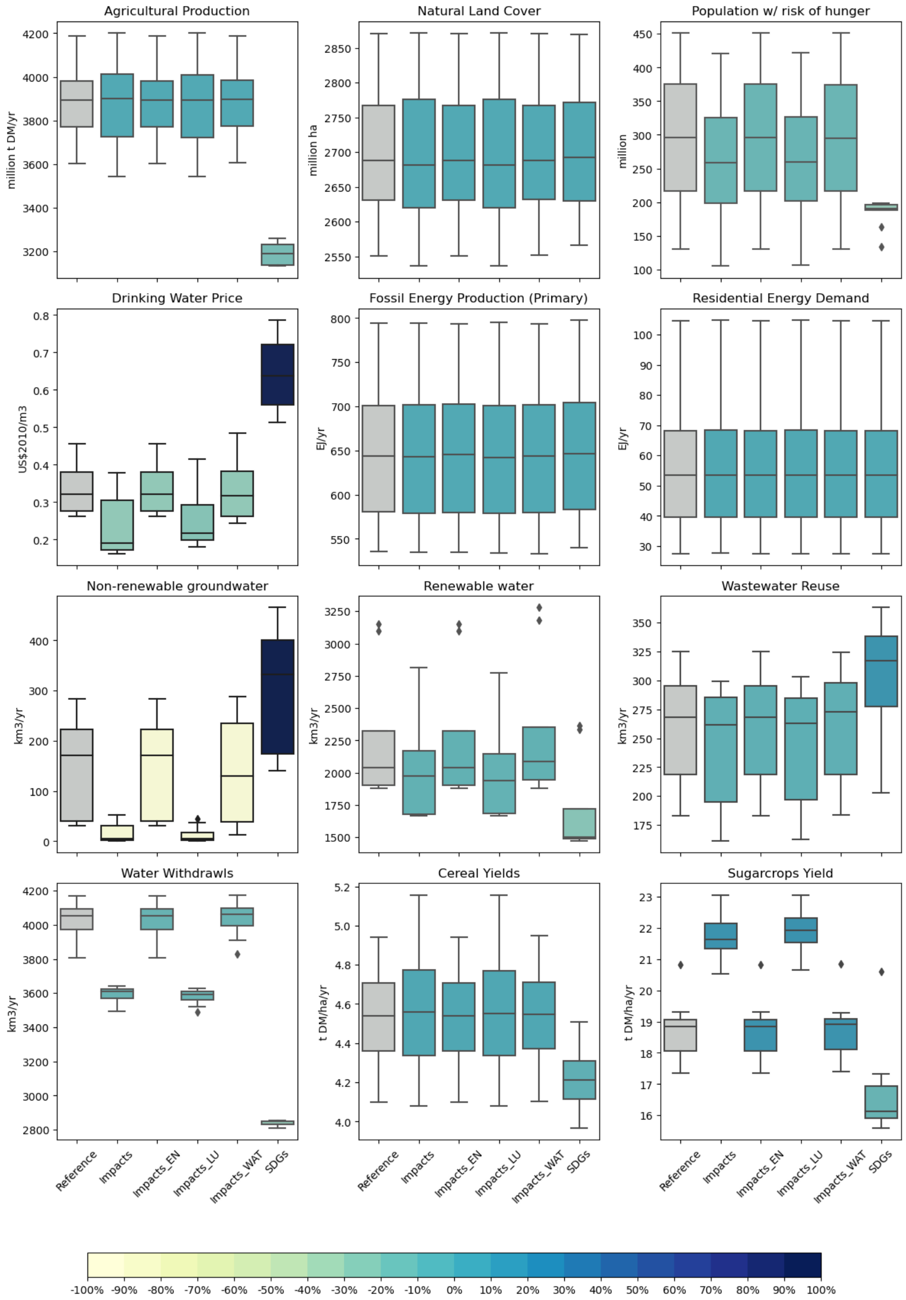


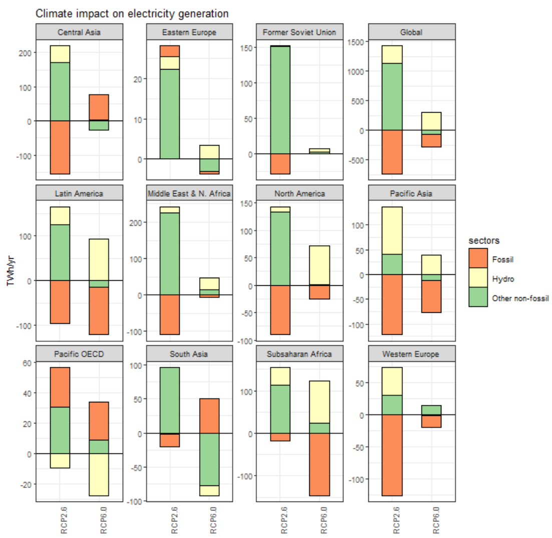
***Figure 5** illustrates the supply and withdrawal components of the global water balance are reported from the model outputs for the Reference and Impacts scenarios. A range of blue hues are used to represent the supply sources, and a range of red hues are used to represent the withdrawals. Water supply 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.*



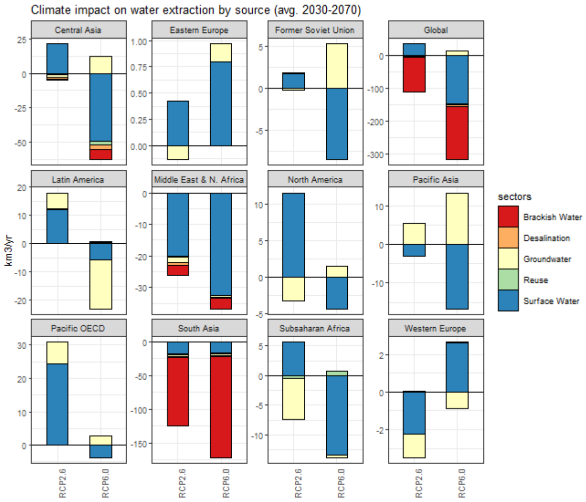
850 ***Figure 6*** *A Comparison of Key EWL Indicators across Multiple Scenarios It shows the boxplot distributions for selected indicators from the model output. From 2030 to 2080, these are*

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.

~~A)~~



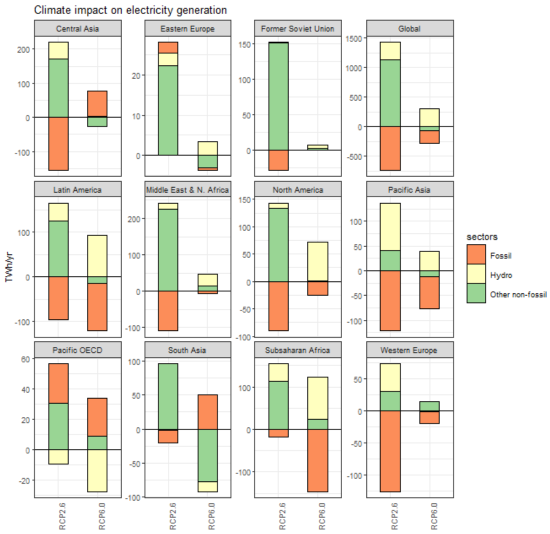
~~B)~~



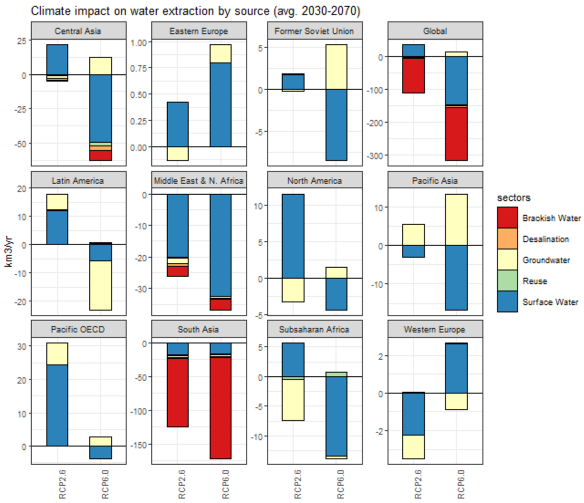
~~Figure 6 A) Climate impacts on electricity generation (TWh/yr.). The average of 2030-2070 Supplementary Figure S 4.2 .1 shows the electricity generation in TWh/yr. B) Climate effects on water infrastructure (km3/yr.)~~

It is important to emphasize that the ~~costs~~ 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. ~~To ensure that the solutions offered are solid and trustworthy, the results of this study should be compared with those of other model evaluations.~~ 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 several models.

~~A)~~



~~B)~~



~~Figure 6 A) Climate impacts on electricity generation (TWh/yr.). The average of 2030-2070 Supplementary Figure S 4.2 .1 shows the electricity generation in TWh/yr. B) Climate effects on water infrastructure (km3/yr.)~~

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 is lacking certain aspects and uncertainties. Since we look at the integrated systems as a whole, we do not include inter-basin or spatial unit transfers, which can be crucial for answering transboundary challenges in the river

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Formatted: Justified, Indent: First line: 1.27 cm, Space Before: 0 pt, After: 0 pt, Line spacing: 1.5 lines 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) are greater than those of climate models. The model's representation of alternative water constraints, such as the economic consequences of fossil groundwater extraction as a means 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 subannual 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.

~~Future research will explore additional climate impact dimensions. For instance, the sub-annual temporal resolution must be more tolerant of statistical extremes under various circumstances. In addition, the model's portrayal of alternate water limitations, such as the costs involved with extracting fossil groundwater to limit water usage, will be improved in future versions. Currently, the model does not account for irrigation withdrawals or inter-basin/spatial unit transfers, which might be crucial for basins crossed by MESSAGE areas. In addition, the model does not account for water storage, which may be an essential aspect of water resource management.~~

~~Furthermore, the nexus module depends on various data sources to represent climate effects, which might be challenging to reconcile for consistency. In the future, the model will need to be updated with the most recent data on climate effects, especially considering that the sensitivity of indicators to these impacts and the uncertainty of GHM is more significant than that of climate models. Consideration will also be given to the effect of sub-annual extreme values, which may be averaged out in the yearly study to reduce the impact of extreme behaviours. For more robust analysis, future studies will explore more consistent and reliable data streams from different sectors.~~

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 in regard to water and climate. The water sector results are based on water flow reliability to evaluate the amount of available renewable water that is reliable 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 many 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 considerably 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

Author's Contributions

MA, AV, EB, VK, KR conceived the modelling framework. MA & AV led the model development with support of EB, OF, PNK, KR, and VK. SF, EB, AM helped with the GLOBIOM scenarios. AM provided data on cooling gaps, MPC ran energy access scenarios, PB and YS provided the hydrological data. MM, KR, VK did overall supervision. MA led the manuscript, and preparation of results. AV & EB coordinated the overall research. All authors reviewed and contributed to the manuscript writing.

Data Availability

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

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Competing Interests

The authors declare that they have no conflict of interest.

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