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Research Report

The status of global freshwater resources

Studien zum deutschen Innovationssystem, No. 8-2025

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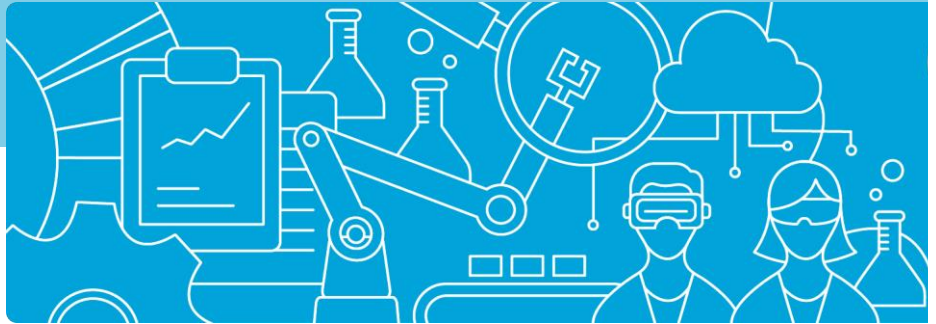
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Robert Luetkemeier, Ahmad Awad

The Status of Global Freshwater Resources



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1. Introduction

Freshwater resources are vital to the survival and prosperity of human societies and natural ecosystems. They play an indispensable role in providing drinking water, supporting agricultural activities, sustaining biodiversity, and enabling industrial processes (Döll et al. 2016). While on the global scale, agriculture is the largest consumer of freshwater (Döll und Siebert 2002), regional hotspots of industrial and domestic demands can put significant pressure on water resources (Luetkemeier et al. 2022). This anthropogenic interference with freshwater systems can threaten aquatic ecosystems that are home to a significant portion of the world's biodiversity (Dudgeon 2014). On the one hand, protecting these ecosystems is important for nature conservation, but also for human health and well-being on the other hand. Access to clean water is a fundamental human right, yet billions of people worldwide still lack reliable sources of safe drinking water and adequate sanitation facilities (UN-Water 2021b). This situation leads to the spread of waterborne diseases, contributing to high mortality rates, particularly among children in developing regions. As global populations continue to rise and economic activities expand, the demand for freshwater resources is expected to increase in many regions, leading to higher pressures on freshwater stocks (Huang et al. 2021). Socio-economic factors, such as population growth, urbanization, and technological advancements, shape water usage patterns and influence resource availability. Concurrently, the impacts of climate change have become more pronounced, altering hydrological cycles and exacerbating water scarcity in many regions worldwide. Altered precipitation patterns and higher frequencies and intensities of extreme weather events such as floods and droughts are already observable (Tabari 2020). This complex setting of anthropogenic demands for water and negative impacts on ecosystems paired with uncertain developments in water availability due to climate change necessitate a comprehensive examination of freshwater resources to ensure sustainable management and equitable distribution.

In order to tackle these challenges, accurate and timely information on the status of freshwater resources globally and on the regional level is key to support informed decision-making. Respective data is, however, not readily available and often scattered over different platforms, institutions and archives. Conflating relevant data repositories to draw conclusions on the most pressing issues is thus required to develop solution pathways. In this sense, innovation in institutional, social and technological fields can help to find more sustainable water use practices with less severe impacts on natural ecosystems. Innovation in the water sector is continuously evolving with significant efficiency gains over the past decades (Gleick et al. 2011) while knowledge on how innovation emerges against pressing challenges of e.g. scarcity is not fully understood (Nyiwul 2021).

Against this background, this project seeks to provide an inventory and projection of freshwater resources in terms of their quantity and quality on a global and regional scale as well as for the federal states in Germany to contribute to the study "Innovation in the Water Sector" funded by the Expertenkommission Forschung & Innovation (EFI).

2. Methodology

For assessing the past, current and potential future status of freshwater resources, analyses were carried out on water stress (water availability and water withdrawals) and water quality. In both domains, a global and regional analysis was carried out as well as a more in-depth investigation of the conditions in the federal states of Germany.

2.1. Water quantity

The assessment of current water availability and possible changes in the future is associated with uncertainty (Reinecke et al. 2021). The same applies to estimating water withdrawal volumes for various sectors (Fiorillo et al. 2021). Since observations for both water availability and withdrawals are scarce, modelling initiatives try to simulate respective processes and thus give an indication of current and potential future changes. For this reason, this project pursued an approach that accounts for the inherent uncertainty of the data by making use of the "Inter-Sectoral Impact Model Intercomparison Project" (ISIMIP) platform, which provides a wide range of modelling results. To account for limitations in ISIMIP's socio-economic projections and resulting water withdrawal simulations, country-specific multiple linear regression models were developed and used for forecasting future withdrawals. Uncertainty in water withdrawal forecasts were considered using multiple scenarios. A general methodological flowchart is represented in Figure 1. Overall, the method was designed and tested among a sample country set that was built upon climate characteristics and socio-economic considerations that have been explored together with the client (priority list) and other contractors in the project (Fraunhofer ISI).

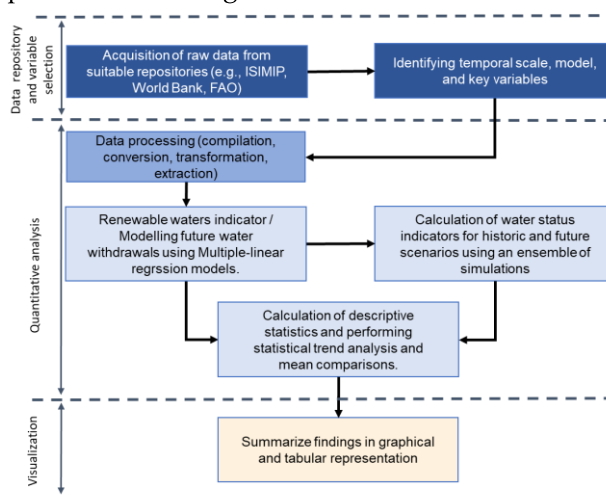


Figure 1: Methodological flowchart for the analysis of freshwater quantity status.

2.1.1. Data repositories

Model data from ISIMIP was used to analyse both historical and future developments in water availability (Warszawski et al. 2014). The ISIMIP platform ensures comparability and overall data availability for all countries worldwide and is thus better suited for this task than existing databases such as FAO Aquastat that, among other things, lack future projections. ISIMIP is a community-driven collaborative effort dedicated to modelling the impacts of climate change. It aims to establish a comparative framework for analysing both specific and integrated effects of climate variations within consistent environmental and socio-economic contexts. The initiative's methodology includes the deployment of sector-specific hydrological impact models and applying bias-corrected climate model outputs. This approach enables a comprehensive and intersectoral evaluation of climate change impacts along with their uncertainties. The effects are represented through an array of metrics, including key hydrological factors (e.g. total runoff, groundwater recharge) and simulations of water withdrawals, providing a global overview of water resources and water demands, considering diverse future emission scenarios on an annual basis.

ISIMIP offers a varied set of variables, starting with the actual climate forcing data via societal drivers down to the key hydrological output variables that are of interest in the current project. While water availability data generated by hydrological impact models were found to provide adequate information for further processing in this project, water withdrawal simulation results revealed unreliable estimates. This was specifically because current withdrawal simulations available do not forecast societal developments into the future, resulting in low model performance. Against this background, ISIMIP's historical water withdrawal data was utilized to train own statistical

models. These models make use of the most recent socio-economic scenario data available from various platforms (Table 1).

Table 1: Overview on data repositories utilized for water quantity analyses.

Database	Host	Data	Releases	URL
Inter-Sectoral Impact Model Intercomparison Project" (ISIMIP)	Potsdam Institute for Climate Impact Research (PIK)	Climate forcing, climate model outputs, impact model outputs	ISIMIP2b (2019) ISIMIP3 (2023)	https://www.isimip.org/
FAO Aquastat	Food and Agriculture Organization of the United Nations (FAO)	Water withdrawals, renewable water resources	Continuously updated	https://data.apps.fao.org/aquastat/?lang=en
World Bank Open Data	The World Bank Group	National water stress, gross domestic product	Continuously updated	https://data.worldbank.org/
Great Acceleration Dataset	International Geosphere-Biosphere Programme (IGBP)	Global water use data	2007	http://www.igbp.net/
World Population Prospects	United Nations	Population data and forecast	2024	https://population.un.org/
DESTATIS GENESIS	Federal Statistics Office of Germany	Population data and forecasts, water use, gross domestic product	Continuously updated	https://www-genesis.destatis.de/genesis/online
EnerOutlook	Enerdata	Primary energy consumption forecast	2023	https://eneroutlook.enerdata.net/
Real GDP long-term forecast	Organisation for Economic Co-operation and Development (OECD)	Gross domestic product forecasts	2023	https://www.oecd.org/en/data/indicators/real-gdp-long-term-forecast.html

2.1.2. Indicator selection

The process of selecting variables from the ISIMIP platform for questions on water availability, withdrawals, and water stress involved (i) identifying key variables most relevant to depict freshwater availability and (ii) reviewing hydrological models from the latest two simulation rounds to find the most reliable models from the diverse set of options.

First, crucial variables for calculating water stress relative to withdrawals were identified. Various indices estimate “physical” water stress by typically considering the relationship between “water availability” and “water withdrawals” (Wang et al. 2021). In physical water stress calculations, water availability refers to renewable water resources within the water cycle, including both “blue water” and “green water” – each with its utility for water resources management. On one hand, blue water stress refers to pressure on renewable surface and groundwater resources (i.e. surface water runoff and groundwater recharge) that are directly accessible for human subtraction (Jewitt 2006; Khand et al. 2021). Such estimates are commonly used for questions related to water allocation, infrastructure planning, and sustainable water withdrawals. On the other hand, green water stress corresponds to water availability estimates of soil moisture for plants to absorb and transpire, as well as soil moisture evaporating from soil surfaces (Hoekstra et al. 2011; Wang et al. 2021). These resources primarily affect the health of ecosystems and rain-fed agriculture and thus, provide utility for agricultural practices, land use planning and ecosystem conservation measures (Jewitt 2006; Khand et al. 2021).

Given the research focus on the relationship between water availability and water withdrawals, the “Water Exploitation Index” (WEI) was employed in the current project, which measures the ratio of total freshwater withdrawals to total available water resources (surface water runoff and groundwater recharge) (Burek et al. 2020; Wang et al. 2021; Casadei et al. 2020). In mathematical terms, the WEI can be interpreted as follows:

$$\frac{\text{Total actual water withdrawals}}{\text{Total available freshwater resources}} \quad \text{Eq. 1}$$

Total actual water withdrawals encompass direct extractions across all sectors (domestic, industrial, irrigation, and livestock), whereas *Total available freshwater resources* are confined to blue renewable water resources (surface water and groundwater recharge). Despite the reliance on non-renewable water resources in various regions, these are excluded as estimates of absolute water storage due to high uncertainties in their estimates. As a result, the project considered the following variables for further analysis:

- *Surface water runoff*
- *Groundwater recharge*
- *Total actual water withdrawals (all sectors)*

The examination of existing hydrological models within the ISIMIP framework focused on the latest two simulation rounds, ISIMIP2b and ISIMIP3b, to identify models capable of providing estimates for the predetermined key variables. A summary of those models, along with the climate-forcing datasets and socio-economic pathways considered, is presented in Table 2. It reveals that the hydrological models from ISIMIP2b do lack important information on total water withdrawals, leaving ISIMIP3b as the final option. In this latest simulation, two hydrological impact models have a compatible structure to retrieve the key variables of interest, namely, the *Community Water Model* (CWatM) and the *H08 model* (Burek et al. 2020; Hanasaki et al. 2018).

Both CWatM and the H08 model, featuring a spatial resolution of approximately 0.5° x 0.5° (roughly 50km x 50km), are recognized as large-scale, state-of-the-art hydrological and water resources models. They are distinguished by their integration of physical water cycle processes, such as precipitation, evapotranspiration, snowmelt, runoff generation, infiltration, and percolation, alongside anthropogenic alteration processes to the water cycle, including withdrawal practices with both total and sectoral estimates (Hanasaki et al. 2018; Burek et al. 2020).

Table 2: Summary of ISIMIP2b and 3b in relation to the key variables of interest.

Group	Variable	ISIMIP Simulation	Impact model (hydrologic model)	Climate related forcing	Climate forcing dataset	No. of simulations
Total renewable freshwater resources	Surface water runoff	ISIMIP 2b	CWatM, CLM45, H08, JULEs-W1, LPJmL, MATSIRO, MPIM, PCR-GLOBWB, ORCHIDEE, VIC, WaterGAP2, WaterGAP2-2c	historical, rcp26, rcp60, rcp85	GFDL-ESM4, IPSL-CM5A-LR, HadGEM2-ES, MIROC5	>30
	total groundwater recharge	ISIMIP 2b	CWatM, CLM45, H08, JULEs-W1, LPJmL, MATSIRO, PCR-GLOBWB, SWAT-VUB, SWIM-NVE, SWIM-PIK, WaterGAP2, WaterGAP2-2c	historical, rcp26, rcp60, rcp85	GFDL-ESM4, IPSL-CM5A-LR, HadGEM2-ES, MIROC5	>30
	Surface water runoff	ISIMIP 3b	CWatM, H08, watergap2-2e	historical, ssp126, ssp370, ssp585	GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, UKESM1-0-LL	15
	total groundwater recharge	ISIMIP 3b	CWatM, H08, watergap2-2e	historical, ssp126, ssp370, ssp585	GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, UKESM1-0-LL	15
Water withdrawals	Total actual water withdrawal (all sectors)	ISIMIP 2b	na	na	na	0
	Total actual water withdrawal (all sectors)	ISIMIP 3b	CWatM, H08	historical, ssp126, ssp370, ssp585	GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, UKESM1-0-LL	15

The CWatM model underwent a global calibration and validation process using observed daily discharge values from 1,366 globally distributed stations within the Global Runoff Data Centre (GRDC) database, demonstrating overall satisfactory performance (Burek et al. 2020). This performance was particularly satisfactory in Europe, South America, and the east and west coasts of North America, although it performed relatively poor in Africa. In contrast, the H08 model did not undergo a similar global calibration and validation (Hanasaki et al. 2018). Instead, its validation was limited to selected basins, where it frequently deviated from observed estimates in most cases. Given the more comprehensive calibration and validation efforts applied to the CWatM model, it has been chosen for further analysis in this project.

2.1.3. Data processing

The key variables from the ISIMIP3b dataset for the CWatM model were processed and visualized using Python's suite of analysis and plotting packages. The initial step involved converting the unit of the downloaded data from kilograms per square meter per second ($\text{kg m}^{-2} \text{s}^{-1}$) to cubic kilometres per year ($\text{km}^3 \text{yr}^{-1}$). Given that the cell areas of the output variables vary by geographic location and at the boundaries between terrestrial and oceanic regions, a cell area mask compatible with the model's specifications was utilized for unit conversion. This process ensures that the analysis is tailored to the spatial resolution and geographic variances inherent in the CWatM model's output. Subsequently, the total renewable water resources were computed using the following equation:

$$\text{Total renewable water res.} = \text{Surface water runoff} + \text{Groundwater recharge} \quad \text{Eq. 2}$$

The derived dataset from the ISIMIP3b CWatM model output was adjusted to span from 1979 to 2100, noting that projections within the dataset extend from 2015 onwards. As such, the historic period is delineated to span from 1979 to 2014 while the future period from 2015 to 2100. A major distinction between these two periods is the consideration of three Shared Socioeconomic Pathways (SSPs) - SSP126, SSP370 and SSP585 - in the future simulations. Each SSP is characterized by a distinct set of conditions, such as population growth, gross domestic product (GDP), land use, and greenhouse gas emissions and includes five simulations to account for variations in model outputs across five different climate forcing datasets.

To discern long-term changes in the availability of renewable water resources, detrending was employed on the *Total renewable water resources* variable. This approach aimed at smoothing out short-term climatic fluctuations while preserving underlying trends that stretches over decades. As such, data was detrended using a 5-year moving average to minimize the effects of short-term climatic cycles (e.g., seasonal changes, El Nino Southern Oscillation, and others). Similar processing steps were applied for the variable *Total actual water withdrawals* (Eq. 3):

$$\text{Total actual water withdrawals (allsectors)} = (\text{dom.} + \text{ind.} + \text{irr.} + \text{livest.}) \quad \text{Eq. 3}$$

Total actual water withdrawals are largely driven by human intervention and are modelled based on data obtained from statistical databases for human consumption, which correlate strongly with various socio-economic drivers such as, population, energy production and consumption, as well as GDP. In general, changes in water withdrawals tend to be more dynamic than water availability as it operates within human timescales. To smooth the curve without eliminating significant

changes triggered by social factors (e.g. regional conflicts or dynamics leading to rapid population growth or decline), a 5-year moving average provided satisfactory results in smoothening non-cyclic trends without strong alteration to overall trends.

Overall, water withdrawal projections have not been used from the ISIMIP repository, as respective data do not include actual projections of socio-economic variables. Therefore, own country-specific and federal state-specific future water withdrawal projections were generated based on statistical multiple linear regression models (MLRs). The MLRs use historical mean water withdrawals (1979 to 2014) as the dependent variable with the following explanatory variables that show good correlation with the dependent variable (Table 3):

- **Population:** Population is a major driving factor in water withdrawals as it scales with population growth. Population numbers are usually one of the key factors when modelling water withdrawals on larger scales (Müller Schmied et al. 2020).
- **Primary energy consumption (PEC):** Improvements in primary energy consumption per capita often arise from technological advancements, such as the implementation of renewable energy sources, improved energy storage solutions, and enhanced energy-saving measures. These advancements result in reduced energy waste and lower consumption per unit of output, reflecting a broader trend towards sustainable resource use. In this study, PEC serves as a proxy to illustrate efficiency gains in resources use.
- **Gross Domestic Product (GDP):** As GDP increases, there is typically a corresponding rise in industrial activity, which often leads to higher water withdrawals. Industries such as manufacturing, mining, and energy production are water-intensive, requiring substantial amounts of water for processes like cooling, cleaning, and production. An expanding economy usually means more factories and industrial facilities, which in turn drives up the demand for water (Müller Schmied et al. 2020).
- **Renewable water resources:** For scaling water withdrawal volumes to country-specific levels, their overall renewable water resources were utilized. Countries with higher renewable water resources tend to have higher withdrawal volumes and vice-versa.

All variables were rescaled to per capita metrics and log transformed. Correlation testing and coefficient of determination (R^2) were calculated to assess the model performance.

Table 3: Pearson correlation coefficient between dependent variable and independent variables used for water withdrawal simulations.

Predicted variable	Predictors	coefficient	p-value
total withdrawals	Population	0.868	<0.005
	GDP (US dollars)	0.454	<0.005
	Primary energy consumption per capita	0.624	<0.005
	renewable water - median	0.438	<0.005

Since the independent variables only provide single future scenarios (except for population projections for Germany, which are based on the latest coordinated population forecast), uncertainty was added to the independent socio-economic variables (PEC/capita, GDP/capita) and climatic variables (renewable waters/capita). The socio-economic variables received an uncertainty envelope of $\pm 5\%$ while for renewable water resources per capita, the 10th and 90th percentile (see section 2.1.4) were utilized. In total, this accounts for 27 future scenarios for water withdrawals up until 2100.

2.1.4. Statistical analysis

Statistical analyses were performed at each time step across the array of simulations. Specifically, calculations were made to determine the mean, median, 10th percentile, and 90th percentile of the stacked data. These statistics served as a foundation for plotting temporal patterns of the variables spanning from 1979 to 2100 for each region of interest. This approach enabled a detailed examination of the variability and trends in water resources and withdrawals over time, offering valuable insights into both historical and projected future scenarios.

The processed datasets for *Total actual water withdrawals* and *Total renewable water resources* were then used to compute the water stress levels per country according to the *Water Exploitation Index*. As a rule, WEI ratios greater than 20% begin to be a limiting factor and create stress conditions (Raskin 1997; Alcamo et al. 2000). Additional categorizations that were adopted in identifying water stress levels using WEI are shown in Table 4.

Table 4: Water stress levels using the WEI (based on Alcamo et al. 2000; Raskin 1997).

Water stress level	WEI (%)	Comments
low	<20%	water demand is significantly lower than available water resources, suggesting that water scarcity is not a current issue.
moderate	20-40%	suggest that there may be a risk of stress during periods of low rainfall or high demand.
high	40-80%	water usage is a significant portion of renewable water resources, indicating potential problems in water supply
severe	>80%	significant scarcity issues and necessitating immediate action to manage water use and protect the ecosystem.

As it is of particular interest to detect the future trend, its intensity and whether it is of significance or not, two time series statistics were applied on the model's future projection period (2015 to 2100). A Mann-Kendell test was applied to detect trends (be they increasing, decreasing, or stable) and assess their significance. The null hypothesis (H_0) of this test posits that the time series exhibits no trend. The selection of the Mann-Kendell test was chosen based on its wide applicability in hydrological and climatologic studies due to its non-reliance on the data following a specific distribution and thus, making it a robust choice for trend analysis (Hamed 2009; Hamed und Ramachandra Rao 1998; Yue et al. 2002).

Second, as means to compare past conditions to current and to distant future ones, three periods were selected for further analysis. These were from 1980 to 1990 ("Past") and from 2015 to 2025 ("Present"), and from 2090 to 2100 ("Future"). Considering that the three periods have unequal variances, a two-tailed Welch's t-test was applied to test whether the means of these periods are significantly different or not while accounting for the uncertainty in each point estimate. The null hypothesis (H_0) assumes that both means are equal. For brevity reasons, this test was applied on the water stress estimates as it captures the combined effect of both water availability and withdrawals. The results of the period's comparison were then represented in tabular and map formats. These statistical methods together offer a comprehensive analysis of future projections compared to past and present, enabling a deeper understanding of the likely evolution of water-related variables.

2.2. Water Quality

The availability of data on water quality is heterogeneous globally, not least because qualitative limitations of water bodies can be caused by a variety of substances and processes (Downing et al. 2021). Therefore, this project explored an inventory of indicators from the Sustainable Development Goal (SDG) data portal for the global and regional scale as well as recent assessments under the Water Framework Directive (WFD) to analyse the water quality conditions in federal states of Germany.

2.2.1. Data repositories

The regional analysis of water quality is primarily based on data obtained from the SDG data portal (<https://www.sdg6data.org/>). This database is an integral part of the United Nations' effort to monitor progress toward the SDGs, particularly SDG 6, which focuses on ensuring availability and sustainable management of water and sanitation for all. The SDG data portal provides national and regional statistical data on a wide range of relevant indicators, providing a comprehensive overview of countries' progress toward achieving sustainable water management. Despite drawbacks in the indicator construction and continuous monitoring schemes (Guppy et al. 2019), the SDG reporting framework employs a standardized methodology to calculate national indicators, ensuring consistency and comparability across countries. By doing so, it allows researchers and policymakers to track progress over time, identify trends, and assess the effectiveness of water management practices on a global scale. The data is updated regularly, offering a dynamic view of water quality and resource management worldwide.

For the national analysis of Germany, data assessed under the umbrella of the Water Framework Directive was used. This regulation can be considered as the most advanced regulatory framework worldwide to protect and restore water bodies (Carvalho et al. 2019). It seeks to establish sustainable management practices for all water bodies across Europe, including rivers, lakes, groundwater, and coastal areas. Its primary goals are to achieve "good ecological, chemical and quantitative status" for these waters by minimizing pollution, protecting aquatic ecosystems, and promoting sustainable water use. The directive advocates for integrated river basin management, cross-border collaboration, and public involvement. River basin management committees must prepare reports every six years. This cycle involves creating River Basin Management Plans (RBMPs) that assess the current condition of water bodies, measure progress toward environmental objectives, and outline necessary actions to maintain or improve the water quality, ecological or quantitative status. The six-year reporting period ensures that plans are consistently updated to incorporate new data, address challenges, and align with current priorities in water management.

2.2.2. Indicator selection

Overall, water quality is a critical aspect for environmental conditions, influencing aquatic ecosystems, human health, and biodiversity. The selection of variables for water quality assessments is, however, subject to a wide range of approaches (Uddin et al. 2021). For the purpose gaining an overview on the quality conditions on a global to regional scale, two SDG indicators were selected:

- **6.3.1: Proportion of Wastewater Flow Safely Treated:** This indicator measures the percentage of wastewater that is treated safely before being released into the environment (UN-Water 2021b). It reflects the effectiveness of sanitation systems and wastewater management practices in each country. Proper wastewater treatment is crucial for preventing

pollution and protecting water quality, making this indicator a key measure of sustainable water management.

- **6.3.2: Proportion of Water Bodies with Good Ambient Water Quality:** This indicator assesses the quality of water in various water bodies, indicating the extent to which they meet established water quality standards (UN-Water 2021a). It provides a measure of the health of aquatic ecosystems and the effectiveness of efforts to reduce pollution and improve water quality. This indicator falls back on the United Nations GEMstat database, which collects water quality parameters globally. The indicator utilizes a set of variables that provide vital information about the chemical, physical, and biological characteristics of water (Warner 2020). It encompasses pH, dissolved oxygen (DO), total phosphorous (TP), total nitrogen (TN), and salinity.

To explore the water quality situation in Germany in more detail, the extensive database available from the WFD framework was utilized (Völker et al. 2022). In this regard, three indicators are relevant that cover both the conditions of surface water bodies and groundwater bodies:

- **Ecological Status of Surface Water Bodies:** This indicator evaluates the health of aquatic ecosystems in surface waters, such as rivers and lakes. It considers factors such as the presence of aquatic life, habitat quality, and hydrological conditions. For heavily modified water bodies, only the ecological potential is considered.
- **Chemical Status of Surface Water Bodies:** This measures the concentration of pollutants and hazardous substances in surface waters. It assesses whether the levels of specific chemicals meet the standards set by the WFD, indicating the potential impact of pollution on water quality.
- **Chemical Status of Groundwater Bodies:** This metric examines the levels of pollutants and chemical substances in groundwater. It evaluates whether these levels meet the required standards, ensuring that groundwater remains a safe and reliable resource for consumption and other uses.

These indicators provide a detailed view of the water quality in Germany, highlighting areas of concern and progress. They cover all relevant surface water bodies and groundwater bodies of the country.

3. Results

The following sub-sections will first look into the results on water stress as composed of water availability and withdrawals. Therein, different spatial scales are considered from the global to the national level. Second, results on water quality conditions are presented, again starting from the global and regional to the national level.

3.1. Water Quantity

3.1.1. Global

The time series plot of global historic and projected renewable water resources exhibit a rather constant development from 1979 to 2014 with a clear shift towards intensification trend for the future (Figure 2 left). The projected future upward trend with a positive regression slope is statistically significant. The data appears to be more variable post 2015 as depicted by the divergence

between the 10th and 90th percentiles, suggesting increased uncertainty in the projections towards the end of the century. In the literature, the intensification and increasing uncertainties in total renewable water resources are similarly expected as a result of global warming (Zhang et al. 2019) and with the periodic variations from this anticipated trend being not unlikely (Koutsoyiannis 2020).

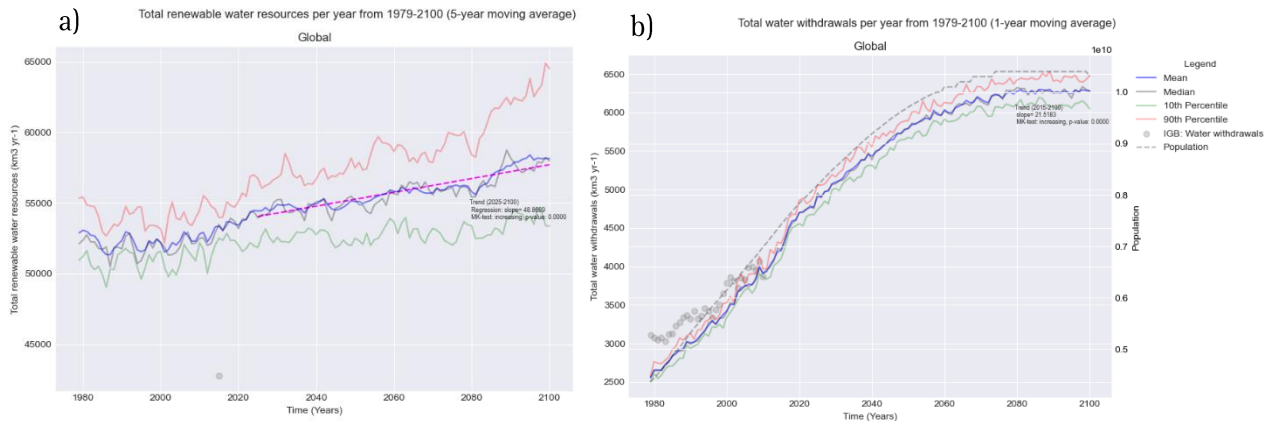


Figure 2: Global water resources from 1979 to 2100 for renewable water resources (left) and water withdrawals as simulated by CWatM from the ISIMP platform and own water withdrawal models (right).

On the other hand, the global plot of total water withdrawals displays a steep increase in the withdrawals from 1980 to 2014 (Figure 2 right). As for the future, a statistically significant logistic growth in global water withdrawals is anticipated under the various climate models, peaking around the year 2080. The slowing rate of increase in withdrawals compared to historic rates is closely linked with global reduced population growth rates (2nd Y-axis in Figure 2 right). Overall, from the MK analysis, the mean of potential future projections demonstrates potential annual withdrawals increase of about 21.5 km³ (21.5 billion m³). That said, various SSPs pathway could exhibit a relatively varying future outcome.

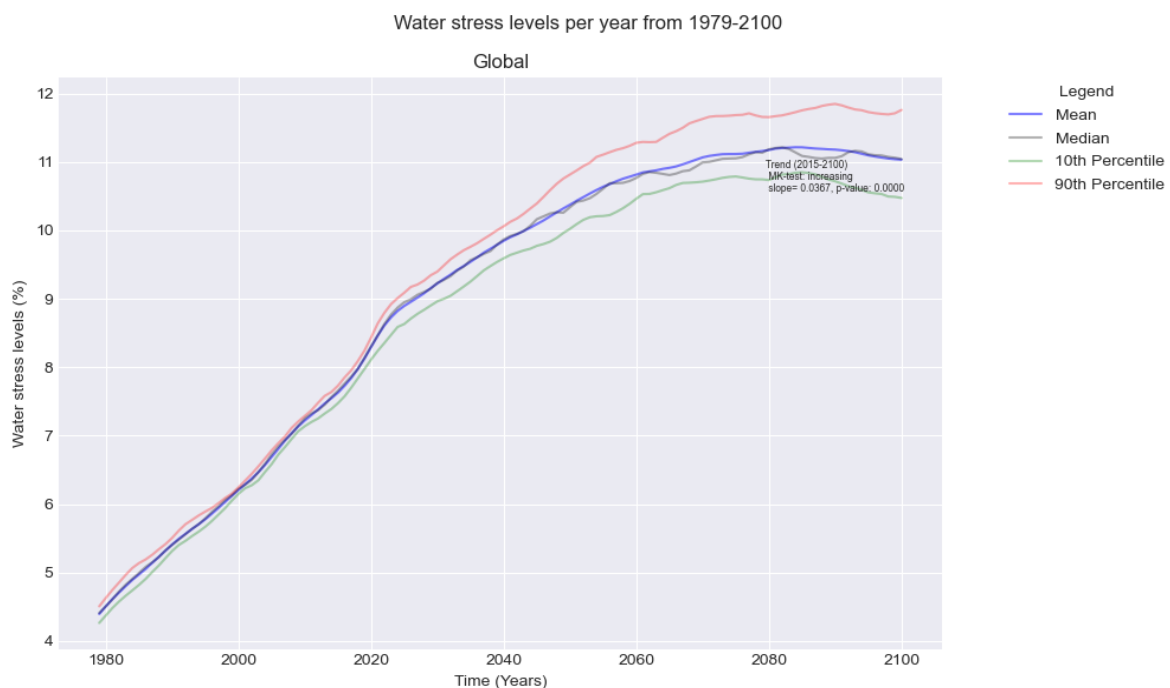


Figure 3: Global water stress calculated as the ratio between renewable water resources and water withdrawals.

Together, the change in global renewables and global water withdrawals translates to a general increasing trend in water stress levels from 1979, peaking around the year 2080 (Figure 3). The time series plot suggests that mean water stress levels are projected to increase over the future, with a high level of statistical confidence. However, the future rate of increase in water stress is milder compared to past conditions. This can be attributed to the projected potential future increase in renewable water resources as well as the reduced growth rates of water withdrawals as time goes by. The tight clustering of the mean, median, and percentile lines suggest a relatively small range of projected outcomes, indicating some confidence in the projections. Overall, throughout the analysed period up until 2040, the stress levels are consistently within low levels (<10%). From 2040 onwards, the global water stress levels are expected to be in the moderate range (10-20%).

3.1.2. Regional

On a regional scale, future trends in renewable water resources manifest differently in varying geographic contexts, suggesting that geographic and climatic factors likely play a significant role in determining the renewable water resources of each country (digital Appendix for all country plots). On the one hand, countries with arid to warm temperate climates are projected to experience a significant reduction in renewable water resources (e.g. Mexico, Figure 4). From these areas however, countries that lie in mid-latitudes reveal a wider uncertainty around their projected mean with no clear trend trajectory. On the other hand, areas in high altitudes (e.g. Canada), areas in the global land monsoon region (e.g. Indonesia), areas with large share of snow climates, as well as large countries with a complex distribution of climate classification (e.g. United States of America) experience a significant positive trend for the projected future mean estimates. However, areas in the southern hemisphere (e.g. South Africa) reveal larger uncertainties. These varying ranges between the 10th and 90th percentile indicate different levels of uncertainty in the projection of each country. Overall, these patterns are in line with existing literature (Greve und Seneviratne 2015; Zhang et al. 2019; Koutsoyiannis 2020).

As for freshwater withdrawals, historic and future levels signal distinct varying patterns between developed and developing or rapidly growing nations (Figure 4 centre). On one hand, developed countries (e.g. Finland) reveal a visible reduction of withdrawals throughout the recent past that continues in the modelled future projections. On the other hand, on average, developing and rapidly growing nations, which compose most of the global population, illustrate increasing patterns that are consistent to that of the global levels. The transitional shift from growing withdrawals to reduced ones in the timespan of a developed nation that is captured in its past trends is also captured in the modelled future withdrawals of developing nations where a peak is reached at a distant point in the future, followed by a reduction in projected withdrawals (e.g. China). Moreover, countries reveal varying ranges between the 10th and 90th percentiles, highlighting different levels of uncertainty in the projection of each country ranges when varying the socio-economic and climatic model predictors. This indicates that certain country withdrawal models are more sensitive to change in predictor variables.

As future water withdrawals and water renewables have complex patterns across the different countries, trends in water stress levels manifest differently but are primarily correlated to the captured patterns in total water withdrawal resources. In addition, the data appears to be more divergent post 2015, as depicted by the variation between the 10th and 90th percentiles, suggesting increased uncertainty in the projections towards the end of the century. These divergent uncertainties vary in each country, indicating different levels of uncertainty in the projection of each country.

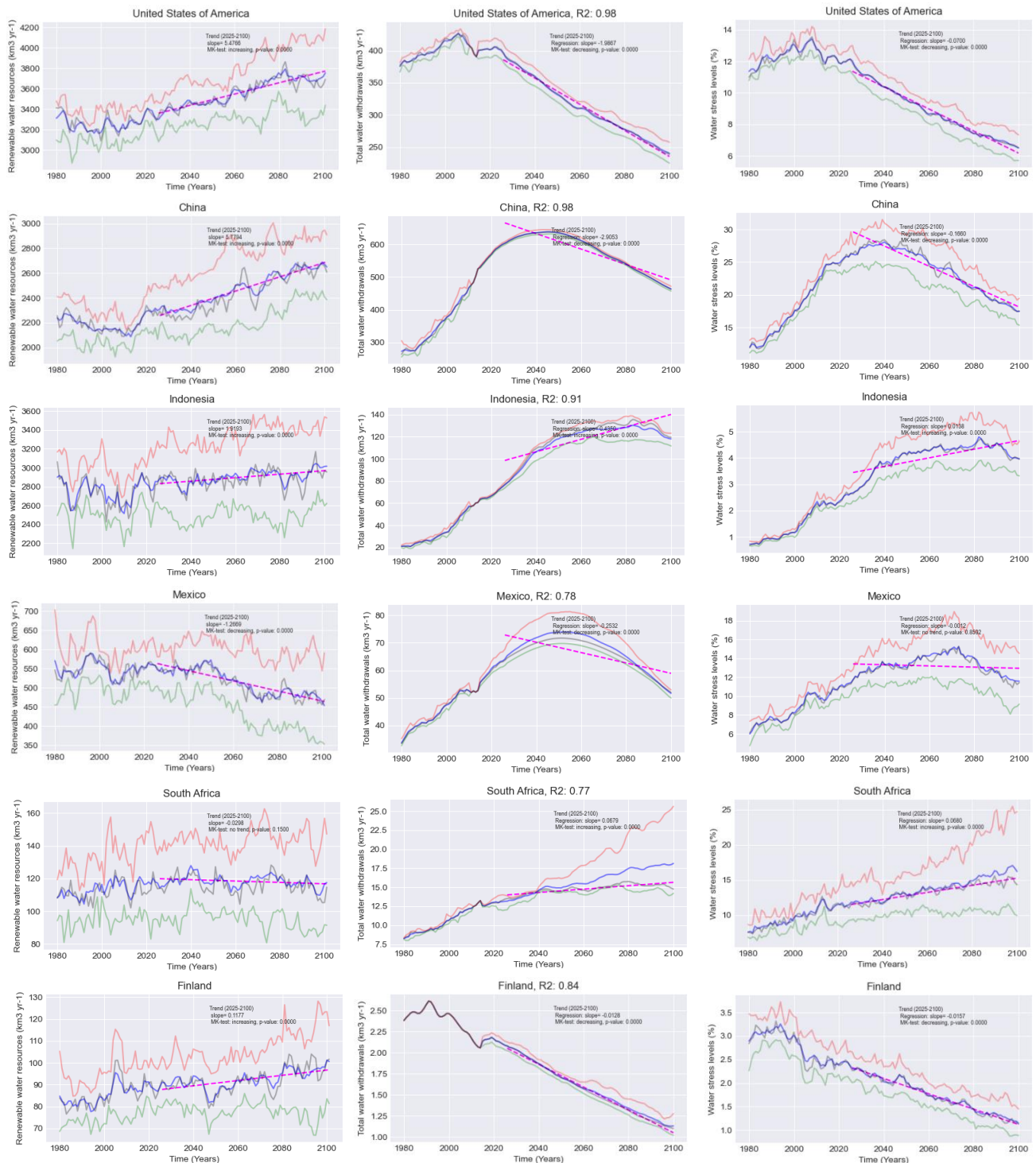


Figure 4: Historic developments and future projections on a regional scale (national boundaries) between 1979 to 2100 for renewable water resources (left), water withdrawals (centre) and water stress (right).

For example, Egypt, Pakistan, Syria, and Jordan show some of the largest increases in mean stress values between present and future, indicating substantial changes in these areas. However, a few regions, e.g., the United States of America, Netherlands, Germany, Canada, Finland, and Saudi Arabia, show a decrease in mean values in the future period compared to the present period. Some of these studied regions' trends, however, exhibit a non-significant change in their mean estimates between the two periods regardless of whether it is a positive or negative shift (e.g. India, Pakistan, Portugal, Australia, Saudi Arabia, and Finland).

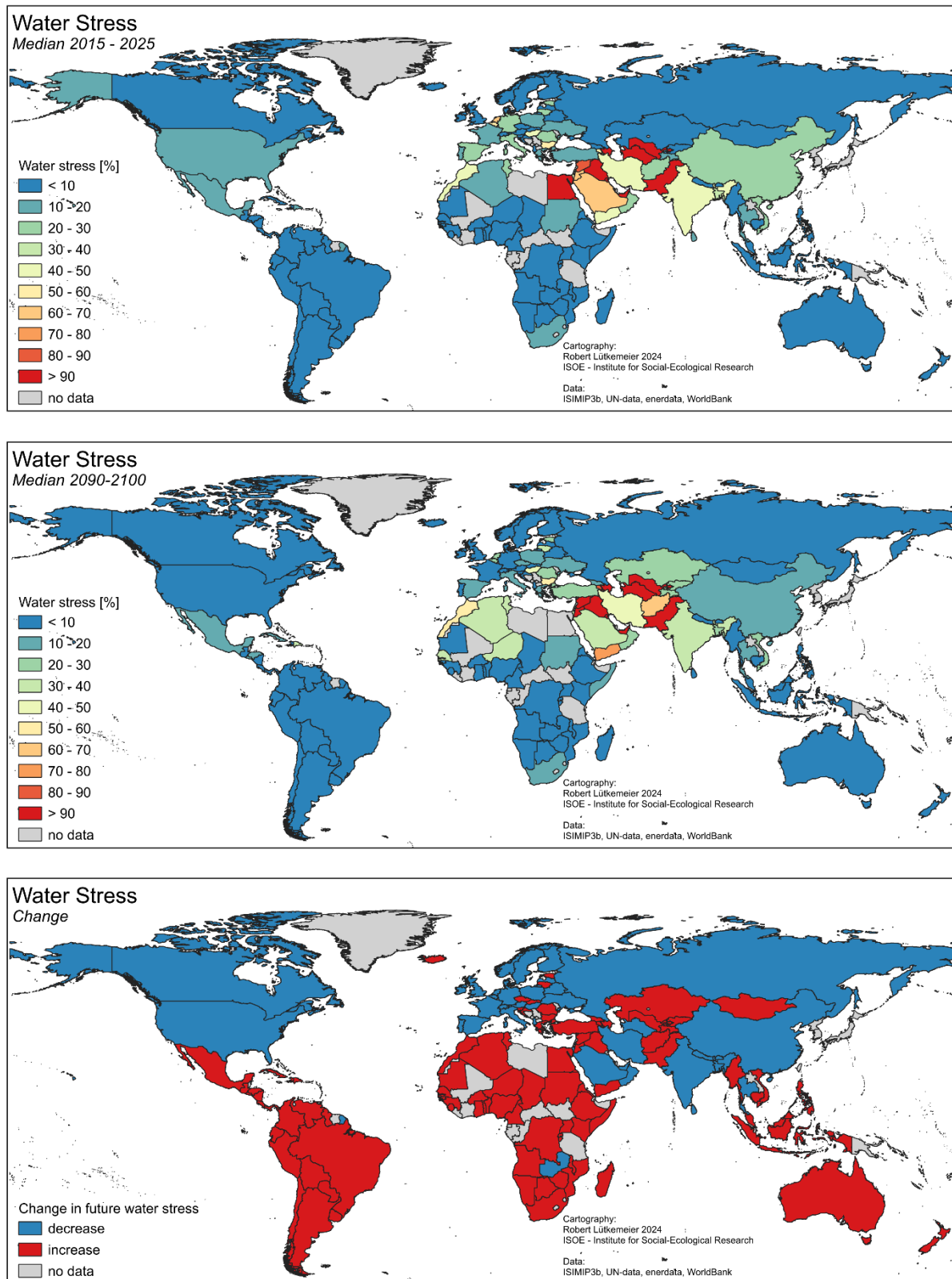


Figure 5: Water stress in the current situation (top), as projected for the future (centre) and the change in water stress (bottom) comparing the future period 2090 – 2100 with the current period 2015 – 2025.

Overall, the analysis reveals that 33 out of the 128 studied countries exceed the 20% water stress threshold for the first period (Figure 5 top). In the distant future (2090-2100), projections indicate an expected increase to 37 out of 128 countries to be experiencing moderate to high stress levels (> 20%).

3.1.3. Germany

Within the German federal states, future trends in renewable water resources exhibit varying trends as a result of local climatic variations between the country's southern states (e.g. Bavaria, Baden-Wurttemberg and Sachsen) and its higher altitudes states (see Figure 6 for exemplary plots). Specifically, southern states such as Bavaria, Baden-Wurttemberg, Saarland, and Sachsen have no significant trend while the rest demonstrate a significant yet mild increasing trend.

That said, all states demonstrate similar water withdrawal trends, i.e. a significantly decreasing trend in the projected future. These states' plots are in-line with the German-wide trend in water withdrawal trajectory as simulated by the ISIMIP analysis. Similarly, such state patterns could be explained by the overall projected reduction in German federal states populations coupled with the projected increase in GDP/capita and reduction in PEC/capita. Overall, the projected change in water withdrawals is more profound compared to changes in renewable water resources in German federal states. As such, projected water stress levels are expected to decrease across all states to fall within the low water stress levels in the distant future (< 10%).

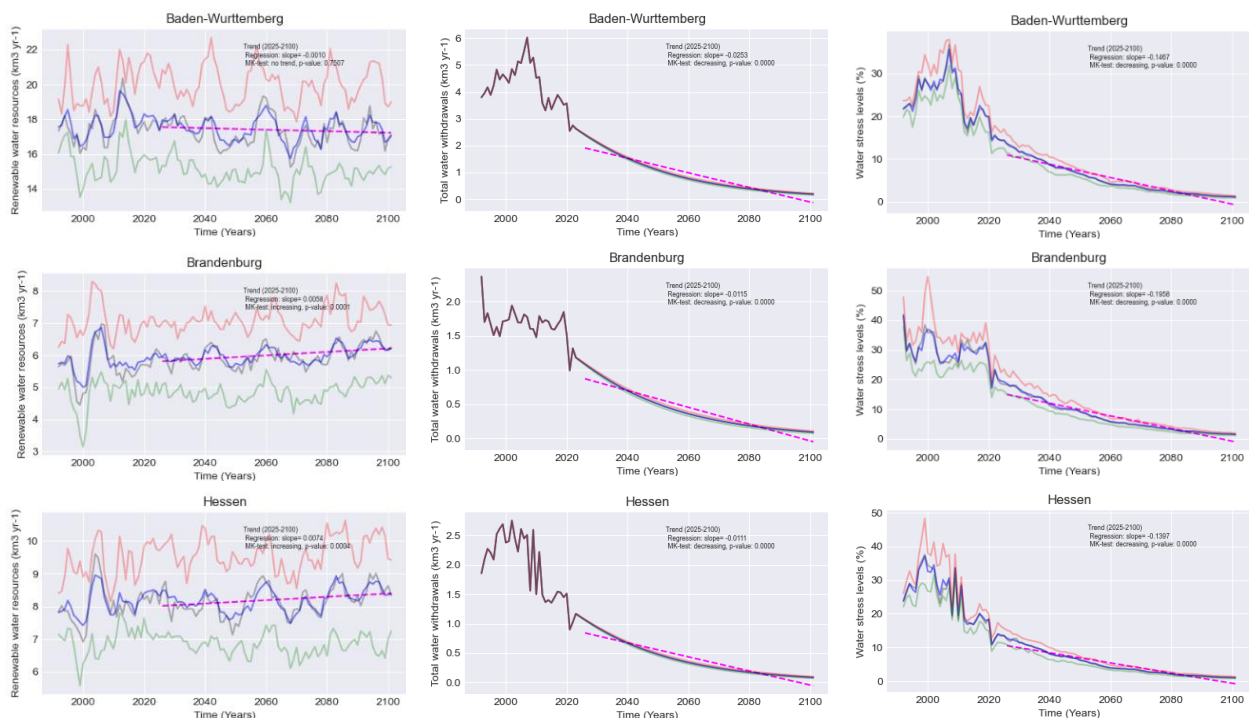


Figure 6: Historic developments and future projections on the German scale (German Federal States) between 1979 to 2100 for a) renewable water, b) water withdrawal, and c) water stress. Due to the coarse resolution of ISIMIP data, federal states of Berlin, Hamburg and Bremen were integrated into the surrounding federal states of Brandenburg and Lower Saxony.

The general trend of decreasing stress from past (1991-2001) to present (2015-2025) is visible except for Sachsen-Anhalt and Mecklenburg-Vorpommern which underwent an increase in water stress between the tested two periods. That said, all states are anticipated to experience a statistically significant reduction in water stress when comparing the future period (2090-2100) with the present water stress levels (2015-2025).

3.2. Water Quality

Water stress as calculated in the previous section is primarily driven by natural water availability and societal water withdrawals. In addition, however, water pollution due to anthropogenic substances can significantly reduce available freshwater stocks usable for human consumption (van Vliet et al. 2021). Therefore, the following two sub-sections present an overview on the current state of water quality on the global and regional scale as well as for the federal states of Germany.

3.2.1. Regional

The monitoring program of the United Nations for the Sustainable Development Goals provides the most comprehensive data repository on water information currently available. In part, it builds upon the global GEMstat database that collects water quality information on key substances. For gaining insights into the current state of water quality, two SDG indicators are considered in the following. SDG indicator 6.3.2 on ‘good ambient water quality’ brings together a set of basic parameters that give vital information about the chemical, physical, and biological characteristics of water bodies. Figure 7 (top) shows the regional pattern of water quality, depicting the share of national water bodies in a good ambient state. Worldwide, 56% of all water bodies show good ambient water quality, when considering the 123 out of 193 countries for which data are available.

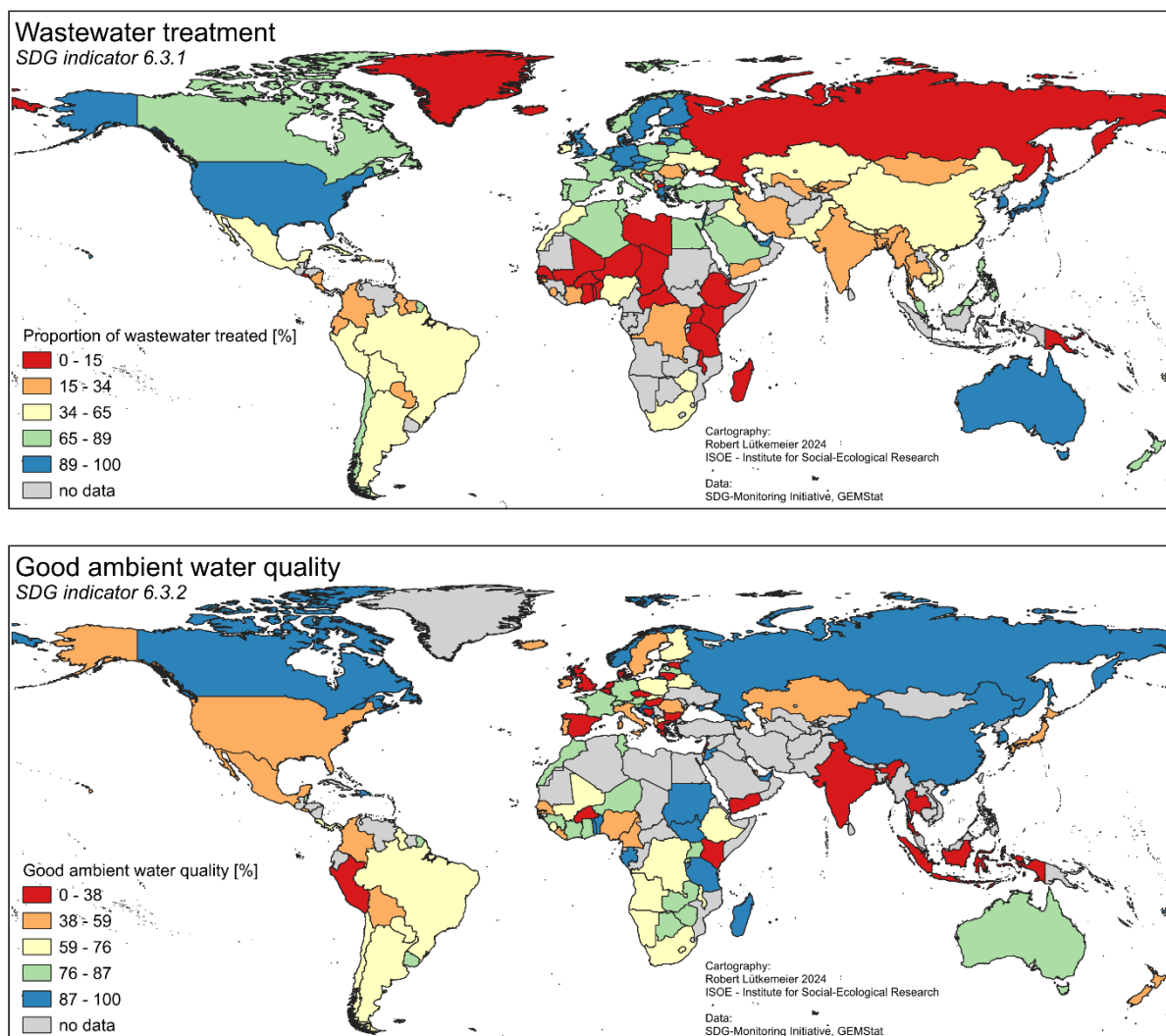


Figure 7: Country-level results of water quality indicators. SDG indicator 6.3.1 on ‘domestic wastewater treatment’ (top) and SDG indicator 6.3.2 on ‘good ambient water quality’ (bottom). Source: SDG data portal 2024.

Globally, the pattern is highly heterogeneous with high quality water for instance in Russia, Canada and Tanzania and low quality conditions in the Netherlands, India and Kenya. This list indicates that economic performance of a country is not necessarily correlated with the respective water quality indicator (UN-Water 2021a). Challenges for water quality are highly diverse and depend on local anthropogenic activities, including pressures from agricultural and industrial processes as well as contamination from wastewater leakage. The original GEMstat database shows that for instance many industrialized countries are suffering from agricultural pollution with high inputs of fertilizers and pesticides (see the example of Germany in section 3.2.2).

Overall, data remains scarce with unknown conditions of ambient water quality for nearly 3 billion people due to the lack of routine data collection (UN-Water 2021a). There are substantial data gaps in Central, Southern, and Western Asia, emphasizing the need for enhanced monitoring capacities. Addressing these deficiencies through improved monitoring and data management is crucial for achieving global water quality goals and protecting human health and ecosystems.



Figure 8: Regional results of SDG indicators 6.3.1 ‘domestic wastewater treatment’ and 6.3.2 on ‘good ambient water quality’. Source: SDG data portal 2024

SDG indicator 6.3.1 on ‘domestic wastewater treatment’ brings in another viewpoint on water quality issues. It gives an indication on the technical ability of countries to clean wastewater and thereby protect water bodies from anthropogenic substances. Globally, 58% of domestic wastewater is safely treated. Figure 7 (bottom), however, shows the strong heterogeneity among the countries worldwide. It becomes apparent that industrialized countries tend to have a higher technical capacity to treat domestic wastewater as compared to developing countries. In Sub-Saharan Africa and Central Asia and Southern Asia, for instance, only 20 - 24% of domestic wastewater is safely treated (Figure 8), posing significant risks for water bodies, the environment and human health.

There is a lack of comprehensive and consistent data due to insufficient monitoring and inconsistent reporting, especially in low- and middle-income countries, which hampers efforts to track

progress toward goal achievement. Significant disparities exist between regions, indicating a need for standardized methodologies, improved data collection, and increased investment in wastewater infrastructure (UN-Water 2021b).

3.2.2. Germany

Data availability and quality for European countries is significantly enhanced as compared to the global and regional scale due to the Water Framework Directive (WFD), implemented in 2000. Based on the most recent data available from the RBMPs for Germany, achieving the ecological goals of surface water bodies remains challenging. Only 9% of the country's surface water bodies meet the criteria for a good ecological status or potential (Völker et al. 2022).

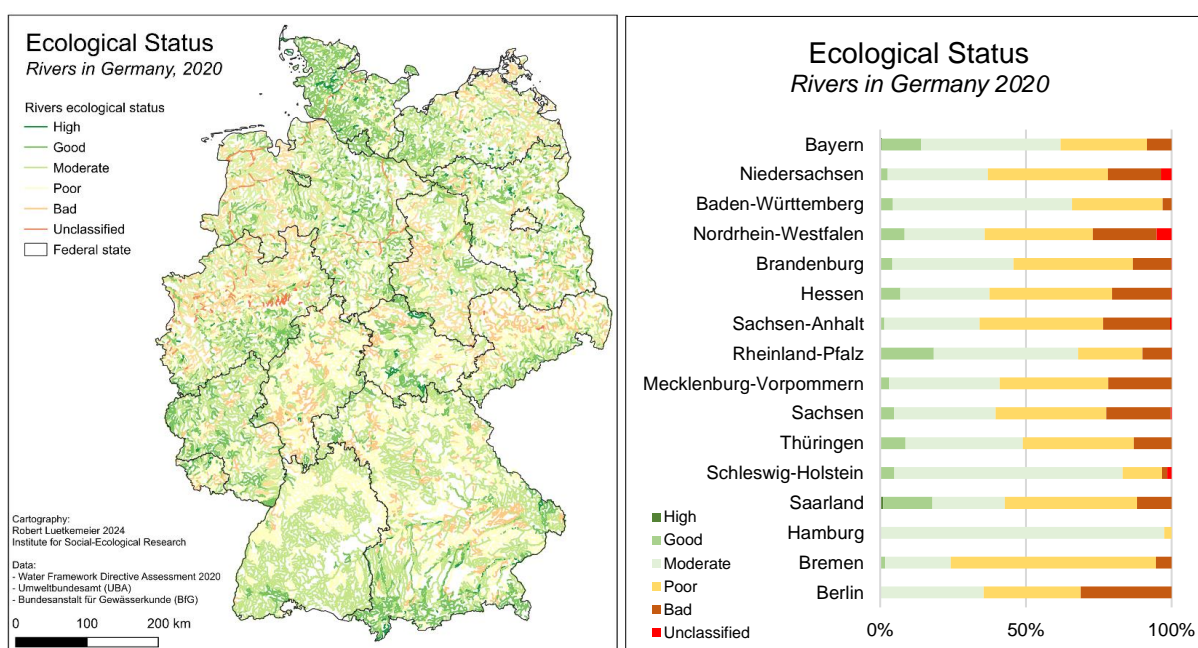


Figure 9: Ecological status of surface water bodies in Germany. Surface water bodies classified according to their ecological status or ecological potential (left). Ecological status or ecological potential aggregated on the federal state level, with a sorting from top to bottom based on total number of surface water bodies (right). Source: Federal Environment Agency based on WFD assessment 2020.

Figure 9 shows the surface water bodies and their ecological status or potential and the aggregated statistics for the federal states. This highlights the significant obstacles in maintaining healthy aquatic ecosystems. Some improvements have been seen in natural rivers, with 13% achieving good ecological status due to better conditions for biological elements such as macroinvertebrates and fish fauna. Efforts to reduce pollution and enhance habitats have contributed to these gains. However, many rivers still face ecological pressures from agricultural runoff, urban development, and industrial discharges. Artificial and heavily modified water bodies (HMWBs) face greater challenges, with only 5% achieving good ecological potential. Human activities like channelization and dam construction disrupt natural habitats, making restoration difficult. Efforts focus on improving connectivity and re-establishing natural habitats. Lakes show a relatively better ecological status, with 20% achieving good status. However, challenges remain with macrophytes and phytobenthos due to high nutrient concentrations from agricultural runoff, leading to eutrophication and harmful algal blooms (Völker et al. 2022).

Several factors impact the ecological status of Germany's surface water bodies. Nutrient pollution primarily stems from agricultural activities, where fertilizers and animal waste introduce excessive

nutrients into water bodies. This causes eutrophication, a process that leads to algal blooms and oxygen depletion, ultimately resulting in the loss of biodiversity. Additionally, hydromorphological alterations due to human interventions, such as modifications for navigation and flood control, disrupt natural ecosystems. These alterations often change the flow and structure of water bodies, affecting habitats and reducing the ability of ecosystems to function properly. Chemical pollution is another major factor, as industrial and urban discharges introduce harmful pollutants into water bodies. Chemicals such as heavy metals and organic compounds can accumulate in the environment and in organisms, posing significant risks to aquatic life and human health. Moreover, climate change further complicates these challenges by altering hydrological cycles and affecting water quality. Increased temperatures and changes in precipitation patterns can lead to more frequent and severe droughts and floods, exacerbating existing pollution issues and stressing aquatic ecosystems (Völker et al. 2022).

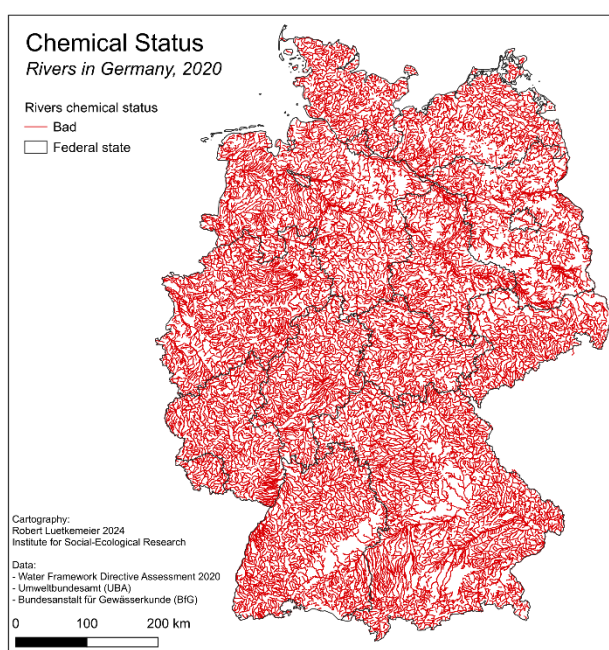


Figure 10: Chemical status of surface water bodies in Germany. Source: Federal Environment Agency based on WFD assessment 2020.

threshold of 50 mg/l, posing a risk to drinking water quality and the overall ecological balance of groundwater-dependent ecosystems. Efforts to address these issues are complicated by diffuse pollution sources and the long-term persistence of contaminants in the subsurface environment (Völker et al. 2022).

To improve the chemical status of both surface and groundwater, Germany is focusing on several strategies, including stricter regulations on pollutant emissions, enhanced monitoring and assessment programs, and the implementation of best management practices in agriculture to reduce nutrient runoff. Additionally, the restoration of natural water bodies and the improvement of wastewater treatment technologies are critical components of Germany's approach to achieving the WFD's goals for good chemical status across all water bodies (Völker et al. 2022). Despite these efforts, achieving significant improvements remains a complex challenge due to the historical pollution legacy and ongoing pressures from urbanization and intensive agriculture.

The chemical status of surface water bodies and groundwater in Germany faces even higher challenges (Völker et al. 2022). For surface water bodies, the chemical status is assessed based on a range of pollutants, including pesticides, heavy metals, and other hazardous substances. Despite efforts to improve water quality, none of Germany's surface waters meets the "good chemical status" criteria set WFD (Figure 10). One major issue is the presence of legacy pollutants such as mercury and polycyclic aromatic hydrocarbons, which persist in the environment and continue to pose risks to aquatic ecosystems and human health.

Groundwater in Germany also shows concerning levels of contamination, primarily from nitrate and pesticide residues due to agricultural practices. Figure 11 shows that the nitrate levels in many regions exceed the

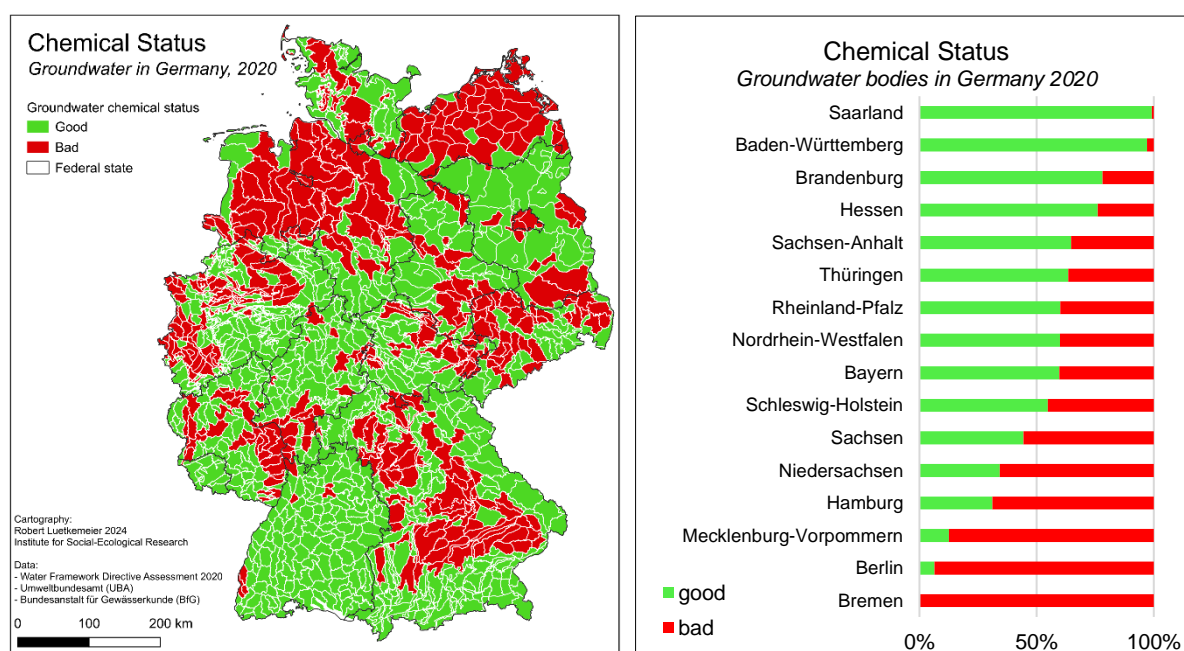


Figure 11: Chemical status of groundwater bodies in Germany. A) Groundwater bodies classified according to their chemical status. B) Chemical status aggregated on the federal state level. Source: Federal Environment Agency based on WFD assessment 2020.

4. Conclusions

Freshwater resources are critical for both environmental health and human societies. Knowledge on the current state and future projections related to freshwater resources is essential to develop innovative solutions. This study looked into water quantity and quality conditions on a global and regional scale as well as the specific situation in Germany.

For assessing the current and future state of water quantity, an analysis of data from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) was carried out to identify past, present, and future conditions of water resources. Water availability data was analysed and own water withdrawals simulations were performed using various socio-economic driving factors to calculate water stress levels today and in the far future. In terms of regional and national water quality situations, global indicators from the Sustainable Development Goals Monitoring program have been analysed alongside monitoring data from the Water Framework Directive to explore the situation in Germany.

Overall, the study identifies significant uncertainty in assessing current water availability and future changes, primarily due to limited observations and varying socio-economic conditions. Modelling efforts reveal that arid and temperate regions are likely to experience reduced renewable water resources, while high-altitude and monsoon areas might see increases. Water stress is likely to increase globally while in Germany, water stress levels are expected to decline due to decreased withdrawals. Despite the uncertainty in renewable water resources and withdrawals, literature clearly states increasing threats from climate change induced extreme events such as droughts and floods.

Water quality remains a critical concern, with diverse challenges across regions. The study used SDG indicators to assess the proportion of wastewater safely treated and the ambient water quality

status of water bodies. Globally, 56% of water bodies meet good quality standards, but significant disparities exist. Developed countries generally exhibit better wastewater treatment capabilities, while developing regions, particularly in Sub-Saharan Africa and Central Asia, face substantial challenges. In Germany, despite advances in pollution control, water bodies continue to struggle with chemical pollutants, nutrient loads, and legacy contaminants like mercury. Germany's surface water bodies face notable challenges in achieving good ecological and chemical status. Only 9% meet the criteria, with significant pressures from agricultural runoff, industrial discharges, and urbanization. Groundwater quality is also compromised by nitrate and pesticide contamination from agricultural activities, posing risks to drinking water safety and ecological balance.

In conclusion, there is an urgent need for integrated and adaptive water management approaches to address the impacts of climate change, socio-economic developments, and pollution. Enhancing data quality and availability, particularly in underrepresented regions, is crucial for reliable projections and informed policy-making. Collaborative efforts involving stakeholders, governments, and technological advancements are essential to achieving sustainable water resource management that meets the needs of current and future generations.

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6. Digital Appendix

- “Results_Regional”:
 - Time series data (plots + data files) on national results for water withdrawals, renewable water resources and resulting water stress
 - Global maps on water quality indicators
- “Results_Germany”:
 - Time series data (plots + data files) on federal state results for water withdrawals, renewable water resources and resulting water stress
 - Plots and figures on water quality indicators