RUB

HYDROLOGIE / WASSERWIRTSCHAFT

RUHR-UNIVERSITÄT BOCHUM

RUB

SCHRIFTENREIHE
HYDROLOGIE/WASSERWIRTSCHAFT

Water Resources as important factors in the Energy Transition at local and global scale

Flörke, M., Onigkeit, J., Oppel, H. (Eds.)

ISSN 0949-5975

32

2021

LEHRSTUHL FÜR INGENIEURHYDROLOGIE
UND WASSERWIRTSCHAFT

32

WANDEL

WANDEL
Water Resources as important factors in the
Energy Transition at local and global scale

Water Resources as important factors in the Energy Transition at local and global scale

Editorial

Editors

Martina Flörke, Janina Onigkeit, Henning Oppel

Citation

Flörke, M., Onigkeit, J., Oppel, H. (Eds.) (2021). Water Resources as important factors in the Energy Transition at local and global scale. Final Report of the joint project WANDEL. Ruhr-Universität Bochum, ISSN 0949-5975

Project Website

www.wandel.cesr.de

ISSN 0949-5975

Bochum, Germany, September 2021

The underlying project of this report was funded by the German Federal Ministry of Education and Research under the grant number 02WGR1430A-H.

The responsibility for the content of this publication lies with the authors.

SPONSORED BY THE Federal Ministry of Education and Research

FONA Research for sustainability

An Initiative of the Federal Ministry of Education and Research GRoW WATER AS A GLOBAL RESOURCE

Water Resources as important factors in the Energy Transition at local and global scale

Final report of the joint project **WANDEL**, funded by the German Federal Ministry of Education and Research (BMBF) within the funding measure 'Global Resource Water (GRoW)'.

WANDEL joint research project partners and authors of the Final Report

Project Partner	**Author**
Ruhr-Universität Bochum Lehrstuhl für Ingenieurhydrologie und Wasserwirtschaft Prof.'in Dr.-Ing. Martina Flörke martina.floerke@ruhr-uni-bochum.de	Martina Flörke Jenny Kupzig
Universität Kassel – 02WGR1430A Center for Environmental Systems Research Apl. Prof. Dr.-Ing. Rüdiger Schaldach schaldach@usf.uni-kassel.de	Anna Schomberg Christopher Jung Ellen Kynast Rüdiger Schaldach
Universität Kassel – 02WGR1430A Fachgebiet Wasserbau und Wasserwirtschaft Prof. Dr.-Ing. Stephan Theobald s.theobald@uni-kassel.de	Swantje Dettmann Sarah Dickel Tobias Vogtmann Stephan Theobald
Leibniz-Institut für Gewässerökologie und Binnenfischerei im Forschungsverbund Berlin e.V. – 02WGR1430B Prof.'in Dr. Sonja Jähnig sonja.jaehnig@igb-berlin.de	Fengzhi He Christiane Zarfl Sonja C. Jähnig Martin Pusch
Universität Osnabrück – 02WGR1430C FZ Institut für Umweltsystemwissenschaft Prof. Dr. Claudia Pahl-Wostl claudia.pahl-wostl@uni-osnabrueck.de	Tobias Landwehr
United Nations University – 02WGR1430D Institute for Environment and Human Security Dr. Zita Sebesvari sebesvari@ehs.unu.edu	Jazmin Campos Zeballos Liliana Narvaez Zita Sebesvari
Wuppertal Institut für Klima, Umwelt, Energie gGmbH – 02WGR1430E Dr. Julia C. Terrapon-Pfaff julia.pfaff@wupperinst.org	Julia Terrapon-Pfaff Peter Viebahn Sibel Raquel Ersoy
KIMA Automatisierung - Gesellschaft für elektronische Steuerungstechnik und Konstruktion mbH – 02WGR1430F Martin Kondring martin.kondring@kima.de	Martin Kondring Dirk Menker Andreas Boyer
WAGU GmbH Gesellschaft für Wasserwirtschaft, Gewässerökologie & Umweltplanung – 02WGR1430G Alexander Lenz lenz@wagu-kassel.de	Alexander Lenz
mundialis GmbH & Co. KG – 02WGR1430H Hinrich Paulsen paulsen@mundialis.de	Hinrich Paulsen

WANDEL joint research project International and associated partner (Praxispartner)

This report and the research behind it would not have been possible without the support of

- German Federal Institute of Hydrology (BfG)
- Wasser- und Schifffahrtsamt Hann. Münden (Germany)
- Regierungspräsidium Kassel (Germany)
- Bayerische Elektrizitätswerke GmbH (Germany)
- Bayerisches Staatsministerium für Umwelt und Verbraucherschutz, Abteilung 5 Wasserwirtschaft und Bodenschutz (Germany)
- Land Oberösterreich, Abteilung Oberflächengewässerwirtschaft, Gruppe Schutzwasserwirtschaft (Austria)
- Uniper Kraftwerke GmbH (Germany)
- Brazilian Agricultural Research Corporation (Embrapa)
- Instituto Agronômico de Campinas (IAC, Brazil)
- Drâa Association of Renewable Energies, Ouarzazate University Ibn Hohr, Agadir (Morocco)
- Ministère de l'Energie, des Mines, de l'Eau et de l'Environnement, Département de l'Energie et des Mines, Direction Provinciale de Ouarzazate (Morocco)
- Agence Nationale pour le Développement des Zones Oasiennes et de l'Arganier (Morocco)
- Haut-Commissariat aux Eaux et Forêts et de la Lutte Contre la Désertification (Morocco)

Summary

Electricity generation uses water locally (at the place where energy is generated), but also at a distance, where the (raw) material is produced or extracted, e.g., to build a thermal plant or to produce the fertiliser used in biomass production. Different energy systems have different water needs, locally and globally. Conducting a water footprint analysis along the entire energy supply chain, i.e., including local and distant water needs, allows for the comparison of water used per generated unit of electricity across different energy systems. Depending on water availability, the amount of water required may or may not restrict electricity generation locally and globally. Changes in future water demand are to be expected between different regions and energy systems, and will likely influence the long-term sustainability of electricity generation, depending on the system and the availability of water. Examples include the predicted shortage of cooling water, with advancing climate change affecting water quantity and temperature, which further influences the effectiveness of thermal plants. These water constraints may limit the expansion of thermal electricity production and thus accelerate the energy transition (*Energiewende)*.

Is water a limiting factor for the energy transition?

It is well known that different energy systems possess different water demands. These, in turn, directly influence the water availability at power plant locations, or – indirectly – in other regions of the world. Direct water consumption, such as for cooling of thermal power plants, or the manipulation of river flows for hydropower generation, influence local water and environmental systems at the location of the power plant. However, impacts on water resources in remote regions, due to, e.g., coal or copper mining, are much less known. These global **'teleconnections'** between energy production and potential water issues cause a conflict between the sustainable development goals **"clean water and sanitation" (SDG 6)** and **"affordable and clean energy" (SDG 7)**. The WANDEL project investigated water consumption along the entire energy supply chains in an integrated and interdisciplinary way in order to evaluate local and global trade-offs and synergies between these two SDGs in a changing environment. Our approach combined local and global analyses for the acquisition of data, formulation of a spatially explicit water footprint, development of energy and water demand scenarios and the assessment of impacts on global water resources. Moreover, the project developed technical instruments and governance tools. These are provided as guidance for decision makers and stakeholders to make them aware of potential negative impacts of different types of energy systems on water resources.

In terms of electricity production, analyses of the WANDEL project show that strategies for transition to clean energy should not only be evaluated according to their potential reduction of greenhouse gas emissions, but should also consider the abstraction and consumption of water and hence **direct and remote impacts on water resources**. However, compared to current conditions, the total amount of water withdrawn and consumed globally will only decrease if the transformation of energy systems is accompanied by an efficiency increase of power plant and cooling technology. Otherwise, water demand increases also in comparison to scenarios with less ambitious decarbonization targets.

How to identify the trade-offs between the water and energy goals?

Conducting a **Water Scarcity Footprint analysis** along the entire energy supply chain, i.e., including local and distant water requirements, allows for the comparison of water used per generated unit of electricity across various energy systems. Specifically, four different power plants, located in three countries (two in Germany, two international), with different energy systems, were analysed as case studies: (i) a **coal power plant** with water cooling on the river Weser, (ii) a **run-of-river power plant** on the Danube, also in Germany, (iii) a **concentrated solar power plant** (CSP) in Morocco, and (iv) the use **of sugarcane bagasse** for electricity production in Brazil. Remote impacts can be traced back in particular to the global extraction of primary resources from mining, forestry and agriculture, as well as the pollution of water resources from waste treatment. Here it becomes clear that already at the planning stages of energy supply systems, the upstream supply chains and the associated possible shifting of problems to other regions should be considered. The water scarcity footprint analyses also illustrate that energy systems relying on renewable resources have a lower impact on water resources than conventional energy systems, but only if the system reuses waste material (i.e., sugarcane bagasse is treated as a waste product). It also shows that, from the perspective of available water resources, a coal-fired power plant performs better in Germany than a CSP power plant in Morocco. However, for a sustainable global energy transition, the focus should not be on individual environmental impacts such as water resources or CO_2 emissions, but on **promoting technologies that have low impacts across a broad range of sustainability criteria**.

The **risk and sustainability analyses** of all case studies show an increasing vulnerability of electricity generation with **increasing frequency of water scarcity and drought events**. Especially in arid regions, water is already a scarce resource and a limiting factor for economic growth and agricultural productivity. Expansion and construction of (large) photovoltaic plants or CSP power plants in these water-scarce areas increase the pressure on already scarce water resources and thus **increase the competition** between the energy sector and agriculture as well as drinking water supply and minimum flow requirements for aquatic ecosystems. In these areas, human and ecosystem health, sustainable energy production and water supply in a changing environment are at risk. As global warming progresses and the projected impacts of climate change continue, some renewable water resources may be negatively impacted and contribute to further scarcity. Although the model results are subject to different uncertainties (e.g., choice of global circulation model and hydrological model; scenario), robust conclusions can be drawn for regions where model results driven by different GCM input show high agreement. A situation of particular concern can be expected for areas in the Mediterranean countries, western Asia, Australia and the USA – they are all impacted by a decrease in water resources.

Biodiversity is another aspect that should be considered when evaluating strategies for the transition to low-carbon energy systems. Analyses have shown that hydropower development will have a disproportionate negative impact on areas which are rich in freshwater megafauna species. In particular, these are regions in South America, South and East Asia, but also in the Balkan region. Sub-basins with a high proportion of threatened species are at risk from the fragmentation of river systems; these are located in Central America, South-East Asia and the Black and Caspian Sea regions.

How to turn trade-offs into synergies?

To address the problems identified, the WANDEL project developed several **tools for technical and governance guidance**. A new approach, the **Environmental Sustainability Assessment**, allows to evaluate the sustainability of anthropogenic processes and upstream supply chains against the background of potential global environmental impacts. This will provide an interface between the established Environmental Impact Assessment and science-based sustainability indicators. Furthermore, a **set of Indicators for Energy and Water Security** were developed. These allow to assess the sustainability of actions, based on the vulnerability of both the water resources as well as the energy system. Furthermore, this approach also considers the institutional capacity in the target regions. A **new Water Management Tool and a Simulator for the Training of personnel** have been developed. These tools ensure an optimal control of water management systems (barrages and reservoirs) and increase the efficiency and security of waterways. Finally, the WANDEL project pursued an **Open Data Approach**. Data generated within the project is provided on the WANDEL-Share platform. The open data policy of the project provides a solid foundation for resilient decision-making in the context of the transition to low-carbon energy systems.

Spatially Explicit Analyses at local to regional levels (or river basin areas) are necessary in order to adequately assess the water use of energy systems and the resulting contribution to regional water scarcity and likely water quality deterioration. This also includes **Life Cycle Assessment indicators** to identify and evaluate potential environmental impacts related to the construction and operation phases. Mining activities put considerable pressure on regional water resources in terms of quantity and quality. In WANDEL, these results were analysed and made spatially explicit in order to identify (adverse) remote impacts along the supply chains. Remote impacts need to be assessed in view of regional water-energy security in order to **avoid problem-shifting** through the use of technologies that cause other potentially negative environmental impacts at the expense of other world regions. The planning of energy supply systems should therefore take into consideration upstream supply chains and potential problem shifting to other regions. We recommend that such concepts should be included in national energy supply concepts as a spatially explicit environmental assessment of upstream supply, in addition to the assessment of economic issues and CO_2 emissions. Technical and governance tools developed in the WANDEL project support the fulfilment of these requirements and will promote the realization of SDG 6 and SDG 7.

Zusammenfassung

Verschiedene Energiesysteme haben einen unterschiedlichen Wasserbedarf, sowohl vor Ort (lokal) als auch in der Ferne (global). Zur Produktion von Elektrizität wird Wasser vor Ort für Kühlzwecke, aber auch in entfernten Regionen genutzt, in denen (Roh-)Material produziert oder gewonnen wird, beispielsweise für den Kraftwerksbau oder die Herstellung von Dünger für den Anbau von Ackerpflanzen. Die Durchführung einer Wasser-Fußabdruck-Analyse entlang der gesamten vorgelagerten Lieferkette, d.h. einschließlich des lokalen und entfernten Wasserbedarfs, ermöglicht den Vergleich des Wasserverbrauchs pro erzeugter Energieeinheit der verschiedenen Energiesysteme. Je nach Wasserverfügbarkeit kann die benötigte Wassermenge die Stromproduktion lokal und global einschränken. Unterschiede im Wasserbedarf sind zwischen verschiedenen Regionen und Energiesystemen zu erwarten und werden je nach System und Wasserverfügbarkeit wahrscheinlich langfristig die Nachhaltigkeit der Stromproduktion beeinflussen. Beispiele hierfür sind eine mögliche Knappheit von Kühlwasser sowie die Auswirkungen des Klimawandels auf die verfügbare Wassermenge und die Wassertemperatur, was wiederum die Effektivität von thermischen Kraftwerken negativ beeinflusst und zu reduzierter Elektrizitätsproduktion führen kann. Wasserknappheiten könnten demnach den Ausbau thermischer Energiewandlung begrenzen und damit die Energiewende beschleunigen.

Ist Wasser ein begrenzender Faktor für die Energiewende?

Es ist bekannt, dass verschiedene Energiesysteme einen unterschiedlichen Wasserbedarf haben. Diese wiederum beeinflussen direkt die Wasserverfügbarkeit an den Anlagenstandorten oder - indirekt – in entfernten Weltregionen. Direkter Wasserverbrauch, wie z.B. zur Kühlung thermischer Kraftwerke, oder der Ausbau und Regulierung von Flussläufen zur Wasserkrafterzeugung, beeinflussen die lokalen Wasser- und Umweltsysteme am Standort des Kraftwerks. Die Auswirkungen auf die Wasserressourcen in abgelegenen Regionen, z.B. durch den Abbau von Kohle oder Aluminium, sind jedoch weit weniger bekannt. Diese globalen **„Fernverbindungen“** zwischen Energieproduktion und potenziellen Wasserproblemen führen zu einem Konflikt zwischen den UN Nachhaltigkeitszielen **„sauberes Wasser und Sanitärversorgung“ (SDG 6)** und **„bezahlbare und saubere Energie“ (SDG 7)**. Im Verbundprojekt WANDEL wurde der Wasserverbrauch entlang der gesamten vorgelagerten Lieferkette mit einem integrierten Systemansatz untersuchten, um lokale und globale „Hotspots“ zu identifizieren. Auswirkungen der Stromerzeugung auf Wasserressourcen (Quantität und Qualität) und damit verbundene Zielkonflikte zwischen den beiden SDGs konnten bewertet werden. Der in WANDEL verfolgte Systemansatz kombinierte lokale und globale Analysen für die Datenerfassung zur Entwicklung eines räumlich expliziten Wasserfußabdrucks, die Entwicklung von Energie- und Wasserbedarfsszenarien und die Bewertung der Auswirkungen auf die globalen Wasserressourcen. Darüber hinaus wurden in dem Verbundprojekt technische Instrumente und *Governance*-Tools erarbeitet. Diese werden als Leitfaden für Entscheidungsträger und Interessenvertreter bereitgestellt, um sie für mögliche negative Auswirkungen der untersuchten Energiesysteme auf Wasserressourcen zu sensibilisieren.

In Bezug auf die Stromerzeugung zeigen die Analysen des WANDEL-Projekts, dass Strategien für den Übergang zu sauberer Energie nicht nur nach ihrer potenziellen Reduktion von Treibhausgasemissionen bewertet werden sollten, sondern auch den Wasserverbrauch und damit **direkte und entfernte Auswirkungen auf Wasserressourcen** berücksichtigen sollten. Auf globaler Ebene führen Energieszenarien mit ambitionierten Zielen für ein kohlenstoffarmes Energiesystem zu einer geringeren Intensität der Wassernutzung. Im Vergleich zu den heutigen Bedingungen wird die Gesamtmenge des weltweit entnommenen und verbrauchten Wassers jedoch nur sinken, wenn die Transformation des Energiesystems mit einer Effizienzsteigerung der Kraftwerks- und Kühltechnik einhergeht. Ansonsten steigt der Wasserbedarf auch im Vergleich zu den Szenarien mit weniger ambitionierten Dekarbonisierungszielen.

Wie lassen sich die Zielkonflikte zwischen Wasser und Energie ermitteln?

Die Durchführung einer Wasserknappheits-Fußabdruck-Analyse entlang der gesamten Energieversorgungskette, d. h. einschließlich des lokalen und entfernten Wasserbedarfs, ermöglicht den Vergleich des Wasserverbrauchs pro Energieeinheit über verschiedene Energiesysteme hinweg. Konkret wurden vier verschiedene Kraftwerke in drei Ländern mit unterschiedlichen Energiesystemen analysiert: (i) ein **Kohlekraftwerk** mit Wasserkühlung an der Weser, (ii) ein **Laufwasserkraftwerk** sowie die Stauhaltungskette an der Donau, beide in Deutschland, (iii) ein **konzentriertes solarthermisches Kraftwerk** (Concentrated Solar Power, CSP) in Marokko und (iv) die Nutzung von **Zuckerrohr-Bagasse** zur Stromerzeugung in Brasilien. Fernwirkungen sind insbesondere auf die weltweite Gewinnung von Primärressourcen aus Bergbau, Forst- und Landwirtschaft sowie die Verschmutzung von Wasserressourcen aus der Abfallbehandlung zurückzuführen. Hier wird deutlich, dass bereits bei der Planung von Energiesystemen die vorgelagerten Lieferketten und damit verbundenen mögliche Problemverlagerungen in andere Regionen berücksichtigt werden sollten. Die Wasserknappheits-Fußabdruck-Analysen illustrieren auch, dass Energiesysteme, die auf erneuerbare Ressourcen setzen, geringere Auswirkungen auf die Wasserressourcen haben, allerdings nur, wenn das System Abfallmaterial wiederverwendet (d.h., die Zuckerrohrbagasse als Abfallprodukt behandelt wird). Sie zeigt auch, dass aus Sicht verfügbarer Wasserressourcen ein Kohlekraftwerk in Deutschland besser abschneidet als ein CSP-Kraftwerk in Marokko. Allerdings sollte für eine nachhaltige globale Energiewende der Fokus nicht auf einzelnen Umweltauswirkungen liegen, sondern es sollten **Technologien gefördert werden, die in einem breiten Spektrum von Nachhaltigkeitskriterien geringe Auswirkungen haben**.

Die **Risiko- und Nachhaltigkeitsanalysen** aller Fallstudien zeigen eine steigende Verwundbarkeit der Energieversorgung mit zunehmender Häufigkeit von Wasserknappheit und Dürreperioden. Besonders in ariden Regionen ist Wasser bereits heute eine knappe Ressource und ein limitierender Faktor für wirtschaftliches Wachstum und landwirtschaftliche Produktivität. Erweiterungen und Aufbau von (großen) Photovoltaikanlagen oder CSP Kraftwerken in diesen wasserarmen Gebieten verstärken den Nutzungsdruck auf bereits knappe Wasserressourcen und erhöhen somit die Konkurrenz zwischen der Energiewirtschaft und Landwirtschaft sowie Trinkwasserversorgung und Mindestabfluss für aquatische Ökosysteme. In diesen Gebieten sind die Gesundheit von Menschen und Ökosystemen, die nachhaltige Energieerzeugung sowie die Wasserversorgung in einer sich verändernden Umwelt gefährdet. Die fortschreitende globale Erwärmung und die möglichen Auswirkungen des Klimawandels werden sich zum Teil negativ auf die erneuerbaren Wasserressourcen auswirken und zu einer weiteren Verknappung beitragen. Obwohl die Modellergebnisse verschiedenen Unsicherheiten unterliegen (z.B. Wahl des Globalen Zirkulationsmodells und des hydrologischen Modells, Szenario-Annahmen), so lassen sich doch Aussagen zu besonders betroffenen Regionen aus der Übereinstimmung der Modellergebnisse ableiten. Hier sind Gebiete in den Mittelmeeranrainerstaaten, im westlichen Asien, Australien und den USA von einer Abnahme der Wasserressourcen betroffen.

Die **Biodiversität** ist ein weiterer Faktor, der bei der Bewertung von Strategien für den Übergang zu kohlenstoffarmen Energiesystemen berücksichtigt werden sollte. Analysen haben gezeigt, dass sich der Ausbau der Wasserkraft unverhältnismäßig stark auf Gebiete auswirken wird, die reich an Arten der Süßwasser-Megafauna sind. Dies betrifft insbesondere Regionen in Südamerika, Süd- und Ostasien, aber auch die Balkanregion. Teileinzugsgebiete mit einem hohen Anteil bedrohter Arten sind durch die Fragmentierung von Flusssystemen besonders gefährdet; diese befinden sich in Zentralamerika, Südostasien und in den Regionen des Schwarzen und Kaspischen Meeres.

Wie lassen sich Zielkonflikte in Synergien verwandeln?

Um die identifizierten Probleme anzugehen, wurden im Rahmen des WANDEL-Projekts mehrere **Instrumente zur Unterstützung technischer und *Governance*-Prozesse** entwickelt. Mit dem neuen Ansatz ***Environmental Sustainability Assessment*** ergibt sich die Möglichkeit, die Nachhaltigkeit von anthropogenen Prozessen und vorgelagerten Lieferketten vor dem Hintergrund möglicher globaler Umweltauswirkungen zu bewerten. Damit wird eine Schnittstelle zwischen der etablierten Umweltverträglichkeitsprüfung und wissenschaftsbasierten Nachhaltigkeitsindikatoren geschaffen. Darüber hinaus wurde ein **Satz von Indikatoren für Energie- und Wassersicherheit** entwickelt. Diese erlauben es, die Nachhaltigkeit von Maßnahmen zu bewerten, basierend auf der Verwundbarkeit sowohl der Wasserressourcen als auch des Energiesystems. Darüber hinaus berücksichtigt dieser Ansatz auch die institutionelle Kapazität in den Zielregionen. Es wurden ein **neues Wassermanagement-Tool und ein Simulator für die Ausbildung von Betriebspersonal** entwickelt. Diese Werkzeuge gewährleisten eine optimale Steuerung von Wassermanagementsystemen (Staudämme und Reservoirs) und erhöhen die Effizienz und Sicherheit von Wasserwegen. Schließlich verfolgte das WANDEL-Projekt einen Ansatz **offener Datenverfügbarkeit**. Im Rahmen des Projekts generierte Daten werden auf der online-Plattform WANDEL-Share zur

Verfügung gestellt. Die offene Datenpolitik des Projekts bietet eine solide Grundlage für belastbare Entscheidungen im Kontext der Energiewende.

Räumlich explizite Analysen auf lokaler bis regionaler Ebene (bzw. Einzugsgebieten) sind notwendig, um die Wassernutzung von Energiesystemen und den daraus resultierenden Beitrag zu regionaler Wasserknappheit und möglicher Verschlechterung der Wasserqualität adäquat bewerten zu können. Dazu gehören auch **Life Cycle Assessment-Indikatoren**, um potenzielle Umweltauswirkungen der Bau- und Betriebsphase von Kraftwerken zu erfassen und zu bewerten. Die bergbaulichen Aktivitäten üben hinsichtlich Quantität und Qualität zum Teil einen erheblichen Druck auf regionale Wasserressourcen aus. In WANDEL wurden diese Ergebnisse analysiert und räumlich explizit aufbereitet, um (nachteilige) Fernauswirkungen entlang der vorgelagerten Lieferketten zu identifizieren. Fernauswirkungen müssen im Kontext der regionalen Wasser-Energie-Sicherheit bewertet werden, um eine **Problemverschiebung** durch den Einsatz von Technologien zu vermeiden, die andere potenziell negative Umweltauswirkungen auf Kosten anderer Weltregionen verursachen. Bei der Planung von Energieversorgungssystemen sollten daher die vorgelagerten Lieferketten und mögliche Problemverlagerungen in andere Regionen berücksichtigt werden. Dies sollte in naher Zukunft neben der Bewertung wirtschaftlicher Fragen und der CO_2-Emissionen als räumlich explizite Umweltbewertung Eingang in nationale Energiekonzepte finden. Die im Projekt WANDEL entwickelten technischen und regeltechnischen Werkzeuge unterstützen die Erfüllung dieser Anforderungen und fördern die Umsetzung der UN Nachhaltigkeitsziele SDG 6 und SDG 7.

Table of Contents

1 Introduction

1.1 Context

The 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals (SDGs; 2015; UN, 2016) provide an important roadmap to sustainability for Germany and the world-wide. Owing to the growth of global human population and economic development, there is an increasing demand for energy (Ahmad & Zhang, 2020). Still, substantial gaps in electricity supply exist in many regions (e.g. 770 million people without access to electricity in 2019; (IEA, 2021a). Therefore, ensuring “access to affordable, reliable, sustainable and modern energy for all" has been listed in SDG 7. At the same time, climate change mitigation is also included as an SDG goal (i.e., SDG 13) and pushed to the frontline of discussion among international and national parties. For example, the Paris Agreement was reached in 2015 among over 190 parties at COP 21, aiming to reduce greenhouse gas emissions and limit global warming (UNFCCC, 2015). It will require an increase in the share of renewable energies worldwide; they already reach almost 30% of electricity supply globally in 2020 (IEA, 2021b). Furthermore, within these goals, water and energy play a particular role. Not only do they have their own goals (Numbers, 6 and 7, respectively) but they are explicitly or implicitly connected to many of the other SDGs. In particular, they are linked to each other in that significant volumes of water are needed at different stages of the conventional energy supply chain (Meldrum et al., 2013).

Closely linked to this overarching goal 7 is the energy transition (‘*Energiewende’ in German*) in Germany, where the country already provides more than 40% of its electricity production through renewable energy sources (Destatis, 2021). In 2020, the share of renewable energies in Germany's gross electricity consumption rose to 45.4% (2019: 42.0%). For the first time, renewable energy sources generated more electricity than all fossil energy sources (coal, gas and oil) together (BMWi, 2021). SDG 7.2 demands a substantial increase in the share of renewable energy in total final energy consumption. Meeting this target will require to further accelerate the energy transition by increasing renewable energy in electricity production (but also for heating and in the transport sector).

The goals of the energy transition fit very well with the achievement of SDG 7, but the achievement of this goal can have several limiting factors, including the adequate supply of water (Holland et al., 2015; Mielke et al., 2010). The availability and sustainable management of water should be ensured equally for all (goal 6). Therefore, goal 7 and the energy transition and goal 6 (water) are of central importance.

As there are (considerable) potential conflicts of objectives but also synergies (e.g. water vs. energy vs. food) between the goals and their achievement, the implementation of the Sustainable Development Goals requires mechanisms at all levels of implementation (national, regional and global) to identify, mitigate or avoid potential conflicts of objectives or to promote synergies.

1.2 Problem Statement

Water is a key prerequisite to achieve SDG 7, but water resources are subject to physical limitations, i.e., their availability on the one hand, and competing demands for use on the other. It can be expected that future climatic and socio-economic developments will have a significant influence on water availability and quality, and that the demands for use will be exacerbated. The reorientation of energy supply must therefore be examined at global and regional levels with regard to possible limitations of water resources, and the achievement of the sustainability goals for water and energy should be examined for possible conflicts of goals and synergies.

Although the relationship between water and conventional energy is relatively well known (IEA, 2012), there are still many open questions about the role of water in achieving the energy transition, i.e. the transformation of the world energy system from a fossil-fuel-based system to one based on renewable energy. As many renewable energy systems (EES) require less water than conventional energy systems (KES) (Mekonnen et al. 2015), a first key research question is the relationship between conventional energy systems (KES) and water resources:

1. Will water constraints limit the expansion of conventional energy and accelerate the energy transition (*Energiewende*)?

It is also known that some renewable energy options have water requirements comparable to some conventional energy systems, so an equally important question is:

2. Could water constraints slow down the speed of the world-wide energy transition (*Energiewende*)?

These are the two critical guiding questions that are addressed in this joint project. Under the umbrella of these guiding questions, WANDEL has a narrower and sharper focus to enable the generation of usable results that can be implemented with international and associated partners (*Praxispartnern*).

1.3 Aim of the Project

A better understanding of the impact of energy systems, either from fading out fossil or from renewable resources, on freshwater resources is vital in order to inform mitigation plans that meet the challenges of the energy transition (*Energiewende*) and thereby promote a sustainable and just future.

This report provides local/regional and global analyses of today's impacts of different energy systems on water resources onsite and remotely along their entire supply chain as well as future developments in water uses and cooling water deficits in the year 2040. The analyses focus on four case studies: (i) a coal power plant with water cooling on the river Weser (Germany), (ii) a run-of-river power plant on the Danube (Germany), (iii) a concentrated solar power plant in the Drâa Valley (Morocco), and (iv) a sugarcane mill where the bagasse is used for electricity production in the Rio dos Patos basin (Brazil). These analyses were complemented by a global view on future changes in irrigates areas, climate and electricity generation on freshwater resources and biodiversity.

Results are reported at the global, basin and local scales to provide a geographically specific overview of today's conditions and expected changes. In order to inform climate change adaptation and mitigation needs, changing conditions of water resources and demands of the energy sector (and other users) are placed in the context of the energy transition and related socioeconomic development trends. The report also presents solutions which could help international and associated partners (*Praxispartnern*) and policy makers to cope with the identified trade-offs and synergies between achieving SDG 6 and SDG 7. The results inform a discussion on the development of the energy sector and its possible contribution to water scarcity as well as expected conflicts between climate mitigation and conservation of water resources and biodiversity. Water and energy efficiency improvements are explored in the context of reducing on-site and remote impacts on water resources for avoiding problem shifting of water-related impacts in order to achieve a sustainable energy transition.

1.4 References Chapter 1

Ahmad, T., & Zhang, D. (2020). A critical review of comparative global historical energy consumption and future demand: The story told so far. *Energy Reports*, *6*, 1973–1991. https://doi.org/10.1016/j.egyr.2020.07.020

Ahmad, T., & Zhang, D. (2020). *A critical review of comparative global historical energy consumption and future demand: The story told so far* (Vol. 6). https://doi.org/10.1016/j.egyr.2020.07.020

Bundesministerium für Wirtschaft und Energie (BMWi) (2021). https://www.erneuerbare-energien.de/EE/Navigation/DE/Service/Erneuerbare_Energien_in_Zahlen/Aktuelle-Informationen/aktuelle-informationen.html (Accessed 6th June, 2021)

IEA. (2021, June 18). *Energy intensity – SDG7: Data and Projections – Analysis - IEA*. https://www.iea.org/reports/sdg7-data-and-projections/energy-intensity

IEA. (2021, June 22). *SDG7: Data and Projections – Analysis - IEA*. https://www.iea.org/reports/sdg7-data-and-projections

IEA (2012). *World Energy Outlook 2012*, IEA, Paris https://www.iea.org/reports/world-energy-outlook-2012

Holland, R.A., Scott, K., Flörke, M. et al. (2015). Global impacts of energy demand on the freshwa-ter resources of nations. *PNAS*, 112: E6707-E6716, doi: 10.1073/pnas.1507701112

Mielke, E., Diaz Anadon, L., Narayanamurti, V. (2010). *Water consumption of energy resource extraction, processing, and conversion*. Discussion Paper #2010-15, online: belfercent-er.ksg.harvard.edu/files/ETIP-DP-2010-15-final-4.pdf

Mekonnen, M.M., Gerbens-Leenes, P.W., Hoekstra, A.Y. (2015). The consumptive water footprint of electricity and heat: a global assessment. Environmental Science: *Water Research & Technology, 1*, 285-297, doi: 10.1039/c5ew00026b

Meldrum, J., Nettles-Anderson, S., Heath, G., Macknick, J. (2013). Life cycle water use for electricity generation: a review and harmonization of literature estimates. *Environmental Research Letters, 8* (1), 18pp. doi:10.1088/1748-9326/8/1/015031

Statistisches Bundesamt (Destatis) (2021). *Bruttostromerzeugung 2020*. https://www.destatis.de/DE/Themen/Branchen-Unternehmen/Energie/_Grafik/_Interaktiv/bruttostromerzeugung-erneuerbare-energien.html (Accessed 6th June, 2021)

UN (United Nations) (2016). *Sustainable Development Goals. 17 goals to transform our World*. http://www.un.org/sustainabledevelopment/sustainable-development-goals/

UNFCCC (2015) *The Paris Agreement* (FCCC/CP/2015/10/Add.1). Available at: https://unfccc.int/sites/default/files/resource/docs/2015/cop21/eng/10a01.pdf (Accessed 16th January, 2021).

2 Methods and Tools Applied in the Project

2.1 Environmental Sustainability Assessment

Authors: Alexander Lenz, Anna Schomberg

2.1.1 Comprehensive assessment of environmental impacts

Construction projects can have a significant impact on the environment due to their location, type or size. These include projects that serve to generate energy from conventional or renewable energy sources. In Germany, the main objective of the environmental impact assessment (EIA), a widespread instrument for environmental precaution environmental policy, is to identify, describe and evaluate these impacts from the planning phase. The EIA is thus an instrument that serves to assess and reduce or avoid possible negative local or regional environmental impacts of environmentally relevant projects within the framework of approval procedures.

One of the objectives of the WANDEL project was to carry out an EIA for each of the four case studies in retrospect, in order to identify and compare their environmental impacts related to the construction and operation phase, respectively. This is intended to broaden the focus of the WANDEL questions on the role of water scarcity for the global energy transition, beyond the aspect of regional water scarcity. For the purpose of a comprehensive assessment, additional adverse environmental impacts of renewable electricity generation must be considered. In the WANDEL context this has proven to be challenging because 1) the EIA is designed to be carried out before a project's approval and not afterwards, 2) the four case studies differ strongly in data availability, quality and quantity and 3) the environmental impacts of the four case studies also turned out to be diverse and thus difficult to compare. As a solution, the methodological framework of the Environmental Sustainability Assessment (ESA) was developed. It is based on the requirements and functions of the EIA which are defined by the German Law on Environmental Impact Assessment (UVPG), and on elements of Life Cycle Assessments (LCA) defined by standard 14040 given by the International Organization for Standardization (ISO). An LCA is a „cradle-to-grave or cradle-to-cradle analysis technique to assess environmental impacts associated with all the stages of a product's life, which is from raw material extraction through materials processing, manufacture, distribution, and use" (Muralikrishna and Manickam 2017). The ESA aims to assess the sustainability of anthropogenic activities and their upstream process chains against the background of potential global environmental impacts. As such it serves as an interface between the classic EIA and science-based sustainability indicators in the form of an LCA.

These indicators provide an assessment of quantitative input and output flows, which enables a comparison of different case studies with respect to the severity of the induced environmental impacts. The implementation of LCA methods enables the ESA - in contrast to the EIA - to include the impacts of the upstream chain of a project in its consideration.

2.1.2 Structure of the ESA

The proposed structure of the ESA is deduced from both standard 14040 and Annex 4 of the German *Umweltverträglichkeitsprüfung* (UVPG). As shown in Figure 2-1, it is based on the four phases provided by standard 14040. Those phases with a more descriptive character are to be compiled using a verbal-argumentative approach as it is common in classic EIA. These are phases 1, 4 and 5. Phases 2 and 4 can for the most part be filled with information based on the inventory analysis or the chosen midpoint and endpoint indicators, measuring either along the cause-effect chain or at its end. This is the case for all remote impacts and for those on-site impacts that can be identified and analysed in a mathematical-scientific way. Other impacts, such as on the landscape and local flora and fauna, need to be described by a classic EIA. Hence, some phases need to be filled with a combination of both approaches, as one alone may not be able to depict specific information suitably.

What is more, a fifth phase has been added, providing information about avoidance and compensatory measures being an essential part of classic EIAs and of great value for the protection of resources. They may either be specific project features that help prevent or reduce significant negative environmental impacts or external measures with the same objective or aiming for impact compensation. As the portrayed power stations have already been built and because of the absence of information on implemented avoidance and compensatory measures, phase 5 is not being considered for the four case studies.

Impacts associated with the demolition or subsequent use of buildings and technical facilities (phases 2 and 4) are a relevant sustainability aspect but were beyond the scope of this project.

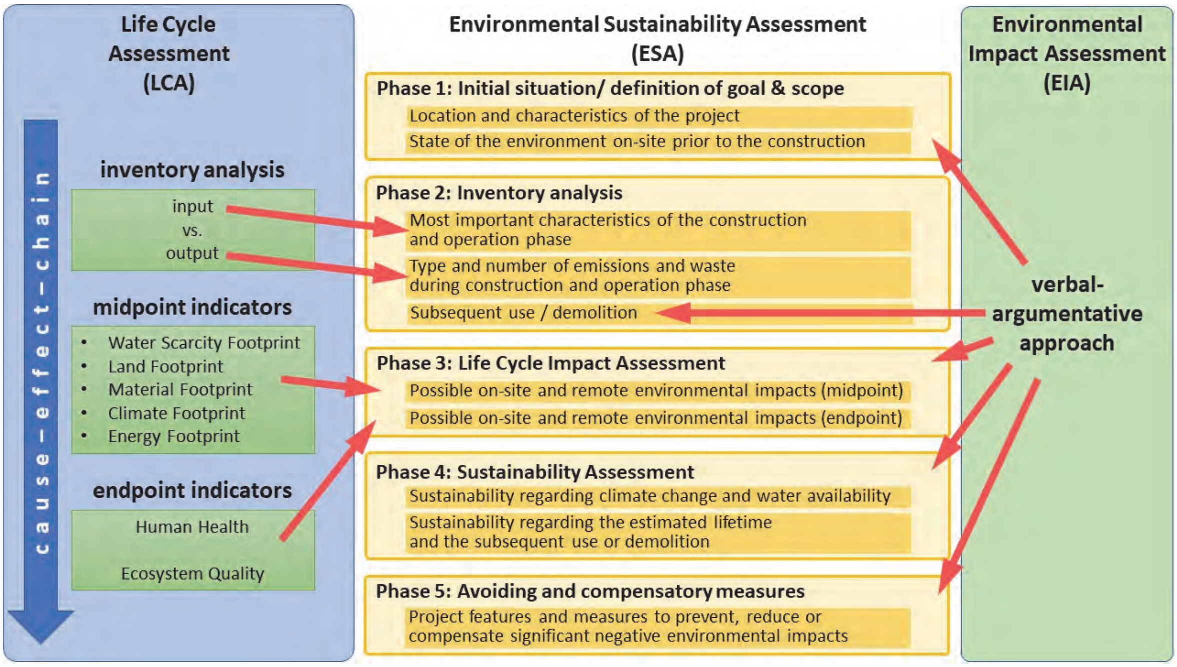

Figure 2-1: Structure of the ESA integrating methods both of LCA and of classic EIA

2.1.3 Selection of suitable indicators for an ESA

To evaluate the impacts of the WANDEL energy systems, seven LCA indicators were included in the ESA, including the climate footprint and the resource footprints, which together already represent over 80% of the environmental impacts (Steinmann et al. 2016). The ecoinvent 3.5 database (Wernet et al. 2016) served as the data basis for the LCA indicators. The data available there was supplemented with case study-specific data. The upstream chains of the mining resources aluminium, iron, gypsum, limestone, coal, copper, lithium, phosphate and clay that had been regionalised as part of the analyses for the Water Scarcity Footprint (WSF, see Section 2.2) were used again as regionalised upstream chains for the ESA.

The results of the LCA indicators are based on those of the life cycle inventory (LCI) and are assigned to the “midpoint and endpoint categories”. It should be noted that the level of aggregation of information and the uncertainties increase from the midpoint to the endpoint indicators (Bringezu et al. 2019). The calculation of the indicators is based on the same LCA models used for the WSF (see Section 2.2), and the determination of hotpots was carried out analogously to the methodology described there. Besides, the impacts are calculated proportionally to 1 kWh of electricity for the construction and operation phases separately and analogously to the WSF.

2.1.4 Description of the selected indicators in detail

For the energy footprint, the indicators fossil cumulative energy demand (CED_{fo}) and renewable cumulative energy demand (CED_{re}) are used. Both are obtained by summarising the values of the sub-categories of the LCIA method cumulative energy demand described by Jungbluth 2007c. The CED_{fo} indicates the energy provided by fossil energy carriers, such as hard coal, natural gas, peat and uranium, and biomass from primary forests along the supply chain. On the other hand, the CED_{re} signifies the energy provided by wood, food residues and biomass from agriculture, wind energy, solar energy, shallow geothermal energy and hydropower. Both indicators contain an assessment of the energy content of the respective energy carriers in MJ equivalents m^{-3}, kg^{-1} or MJ^{-1}. The indicators only evaluate the energy content of energy carriers. The impacts associated with the demanded infrastructure for mining, transportation, etc. are ideally considered by other indicators.

The indicator ecosystem damage potential (EDP) represents the determination and assessment of the land footprint. Land occupation and transformation are included in the LCI as elementary flows. The assessment is carried out with the help of characterisation factors from Koellner and Scholz (2007a, b). Hereby, each land use type is assigned a specific value per m^2 of land used so that land-use changes (transformations) influence the value of areas. The area values are based on the mean number of vascular plants, endangered vascular plants, mosses and molluscs found there. It is assumed that these groups represent the diversity of other species groups. The duration of the change in land use and the time needed to restore the natural state are also taken into account. The EDP is expressed in points kWh^{-1}. Although the number of approaches is still limited, other land footprint methods exist. Moreover, the EDP indicator is endpoint-oriented, in contrast to the actual claim of the land footprint (Figure 2-1). However, due to its ease of use and the existing implementations for the LCA, it has been chosen here.

The climate footprint is represented by the indicator global warming potential 100a (GWP100) within this framework. It is described by Jungbluth (2007a; b), while the used LCA indicator is based on newer IPCC data from 2013. Assessment is carried out with substance-specific values in CO_2-Eq kWh^{-1} for several climate-active substances (CO_2, CO, $CHCl_3$, C_2H_6, CH_4, SF_6).

The product material footprint (PMF) is used to quantify the material input required for the construction and operation phases of the case studies. The indicator raw material input (RMI) summarises the abiotic primary input, i.e. the material that is needed along the entire supply chain in the construction and operation phases, respectively. The indicator total material requirement (TMR) additionally considers the unused extraction, such as overburden from mining. For the assessment of the material supply, each abiotic resource is assigned a specific value that indicates how much mass must be moved to extract 1 kg of the respective resource (Mostert and Bringezu, 2019). The results are expressed in kg kWh^{-1}.

The water scarcity footprint (WSF) is described in Section 2.2. It takes into account the quantitative water use WSF_{quan} resulting from evapotranspiration, water transfers beyond basin boundaries and product-incorporated water along the entire supply chain. In addition, qualitative water use WSF_{qual} is calculated as the dilution volume that is required to dilute aluminium emissions introduced into water bodies along the entire supply chain below a certain threshold. The assessment is carried out with respect to regional water scarcity (see Section 2.2 for the general procedure of LCIA).

The ReCiPe method presented by Hischier (2010) serves to record the impacts of the case studies on the protected goods ecosystem quality (ECO) and human health (HuHe) as defined in the LCA framework. These are endpoint considerations, whereby the impacts are expressed in points kg^{-1}, m^{-2} or $m^{-2}\ a^{-1}$. ECO and HuHe combine several sub-categories such as eutrophication, ecotoxicity and land use or ozone depletion and particulate matter formation.

2.1.5 Application of the ESA in the WANDEL project

Within the WANDEL project, an ESA was performed for each of the four case studies in retrospect following the methodology explained above. Large sections of the LCA analysis took place simultaneously with the evaluations for the newly designed WSF (see Section 2.2). The identified direct and indirect impacts on water resources and on the environment are described in detail in Chapter 3. General findings from the analyses of environmental impacts and a comparison of the four case studies can be found in Section 3.5.

2.2 Water Scarcity Footprint (WSF)

Author: Anna Schomberg

2.2.1 Existing water footprint concepts

Water footprinting has become an important tool for quantifying and assessing human water use and associated environmental impacts. This is a well-known and frequently used concept that has been described by Hoekstra et al. (2002, 2011). It defines three sub-indicators for the water footprint (WF): the first is blue water use, which comprises evaporation from ground- and surface waters, water transfer to different basins and product-incorporated water as a result of human water use. It is hence human water consumption, not water withdrawal. The second is green water, which is often described as sum of evapotranspiration from soils and plants as well as of water incorporated in plant products as a result of human water use. The third is grey water, which describes the volume of water theoretically needed to dilute man-made emissions in water to stay at natural background concentrations or below a generally valid concentration threshold. However, according to this concept, the WF does not take into account the regionally varying availability of water or other potential environmental impacts of water use.

As water scarcity is a regional or local phenomenon (Alcamo et al., 2003), a number of different WSF concepts have been developed in recent years. In various ways, these concepts consider regional water availability and assess the purely quantitative water volumes with corresponding water stress indicators (Alcamo et al., 2007, Pfister et al., 2009, Boulay et al., 2011, Berger et al., 2014, Boulay et al., 2018). Another important development was the calculation of WSFs of not only individual products but of entire global product supply chains with the help of LCAs using corresponding life cycle inventory (LCI) databases. In the course of this, water stress indicators have been implemented in the life cycle impact assessment (LCIA) as characterisation factors and can be used when performing an LCA.

2.2.2 Requirements for an adapted WSF concept

However, due to the various existing concepts, conceptual inconsistencies are still present, which became obvious when a suitable method had to be selected for the WANDEL project. WANDEL aimed to determine whether regional water scarcity for electricity generation could accelerate the implementation of a global transition to renewable energy. To answer this question, it was particularly necessary to compare different electricity generating systems in terms of their water consumption and against the background of regional water supply. The selected WANDEL case studies strongly differ in both aspects. For example, one case study used water for cooling a thermal power plant, and in another one, water was used for irrigation to produce energy from biomass (see Chapter 3). Two case studies were conducted in water-rich Germany and one in Morocco, which has a tense water situation.

Upstream chains had to be explicitly considered to assess not only the direct impacts of the case studies on local water resources but also indirect impacts through the supply of essential, globally traded raw materials. For a meaningful comparison, sub-indicators for human water use that describe all forms of water use against the background of hydrological availability were needed as well as a consequent regionalisation of process locations for an assessment of regional water scarcity. Therefore, it was decided that the scope of the WSF concept would have to be extended within the project (see Schomberg et al., 2021).

The requirements for the adapted WSF are defined as follows. In order to determine spatially explicit WSFs of product supply chains, this study had to overcome the following issues: (1) differing classifications of the risk associated with human water consumption, (2) the absence of a comprehensive conceptualisation of water use in LCA within a consistent hydrological framework and (3) the lack of regionalisation of the indirect impacts (Schomberg et al., 2021). The first point is an indispensable first step and starting point for the concept development; existing studies do not employ to a common classification of the risk associated with human water consumption, although it sets the framework for the goal and scope of a life cycle-wide WSF.

2.2.3 Concept of the life cycle WSF

A basic condition for risk classification has been seen in a systematic description of the interaction between drivers, pressures and state (Drivers-Pressures-State-Impact-Response (DPSIR) framework by Smeets and Weterings, 1999) for human freshwater consumption. The anthroposphere is the driver that puts pressure on the state through inputs into its system and outputs into the environment, while the natural hydrological flow system is the state.

Figure 2-2 illustrates this interaction on a river basin level. From this relationship is derived what is to be considered an impact in general, namely any change of natural freshwater availability as a direct consequence of water-related inputs and outputs. To evaluate the criticality of this change in a second step, a comparison with reference values is necessary. As a basis for defining these references we use the Sustainable Development Goals (SDG), which are an important framework condition in WANDEL. Hence, an impact is defined as the risk of an exceedance of these references, called the Safe-Operating-Space (SOS). Expressed in numbers, this is a water withdrawal-to-availability ratio greater than 0.4 (Alcamo et al., 2007, Schomberg et al., 2021).

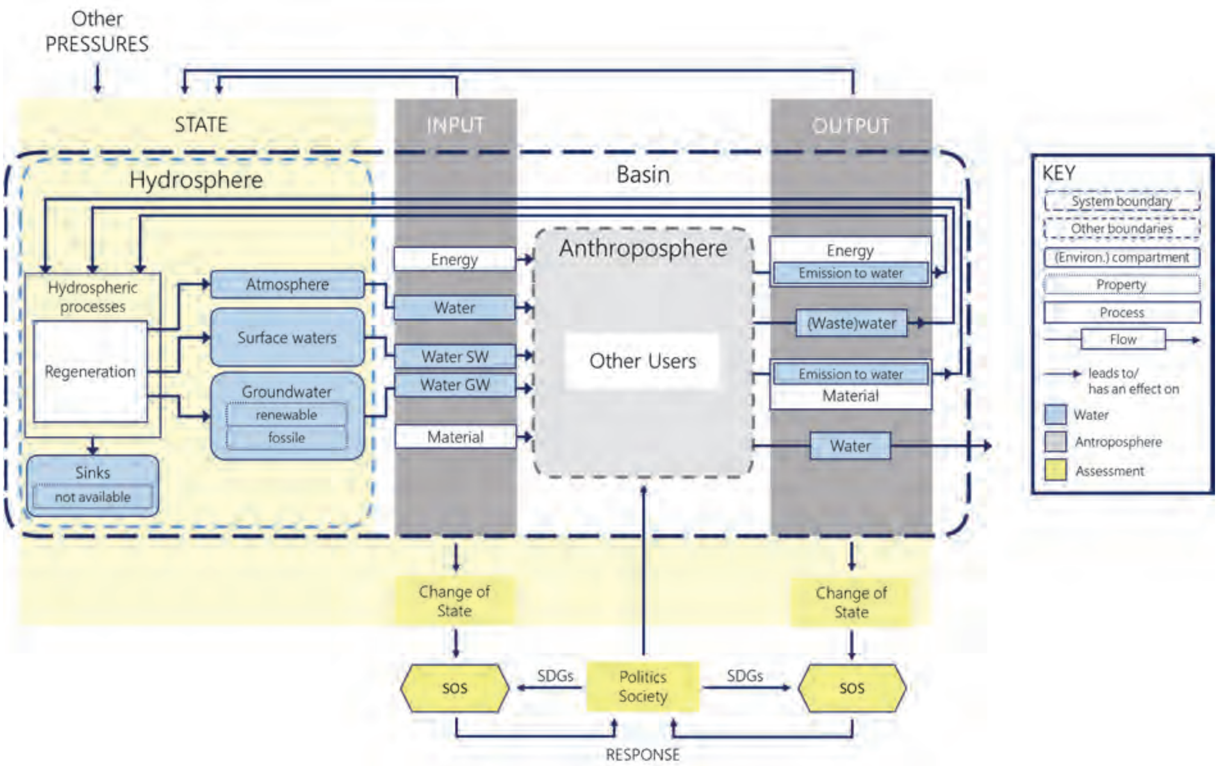

Figure 2-2: Classification of the risk from human water consumption. Interaction of drivers (anthroposphere), pressures (input, output), state (hydrosphere), impacts (change of state) and response (SDGs) for human water consumption according to the DPSIR approach.

With these considerations in mind, the risk from human water use can be classified as a potential change in natural freshwater availability that exceeds the SOS, which thus indicates the risk of freshwater scarcity for humans and nature. It is expressed in volumes of available freshwater remaining (Schomberg et al., 2021). A WSF determined within this classification assesses the probability of on-site and remote natural freshwater scarcity for humans and nature caused by water use along human supply chains in a spatially explicit way (Schomberg et al., 2021).

In the second step, new WSF sub-indicators have been derived from a hydrological balance (Figure 2-3). The quantification has been carried out on a grid level, as grid cells (5 x 5 arcminute spatial resolution) represent the smallest unit in global hydrological models, this offers one the opportunity to use modelling data and to upscale depending on the scope of a study. Figure 2-3 is based on the work of Boulay et al. (2018), where the water storage on the grid cell level is defined as (water) availability-minus-(water) demand (AMD_i). Water-using processes interact with this storage so that the new storage $AMD_{i,t=x+1}$ can be defined as follows (Eq. 2-1):

$$AMD_{i,t=x+1} = AMD_{i,t=x} + in_{aw} + p_{aw} + out_p - in_p - e_{aw} - out_{aw} \quad \text{(Eq. 2-1)}$$

The index 'i' represents the respective catchment area. AMD_i is determined by the inflow from upstream cells in_{aw}, precipitation p_{aw}, outflow from water-using processes to AMD_i out_p, water intake by water-using processes in_p, evapotranspiration e_{aw} and outflow to down-stream cells out_{aw}.

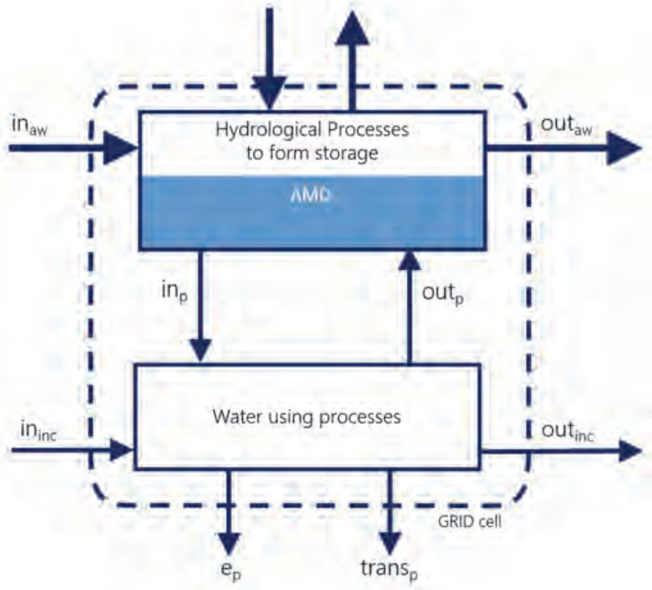

Figure 2-3: Hydrological balance of natural and process-related water flows. Balance of natural water flows and deduction of the 'availability-minus-demand' AMD_i as introduced by Boulay et al. (2017).

AMD_i is determined for each grid cell by balancing the sum of the aforementioned flows, respectively, i. e. there is no distinction between different sources of water, types of water use or water users. Balancing $AMD_{i,t=x+1}$ with the general equation $m_{t=x+1} = m_{t=x} + dm\, dt^{-1}$, where m represents a stock, t = x at a certain point in time and t = x+1 at a later point in time, results in Equation (Eq. 2-1) (Schomberg et al., 2021). As an impact is any change in this storage that exceeds the SOS, all interactions that may cause a change must be reviewed. Figure 2-3 reveals four water flows (arrows) to which this applies: process-related evapotranspiration (e_p), process-related water transfers ($trans_p$), product-incorporated water (out_{inc}) and return flow (out_p).

$$in_p + in_{inc} - e_p - trans_p - out_{inc} - out_p = 0 \quad \text{(Eq. 2-2)}$$

However, the latter does not refer to the quantity of returned water, but its quality, namely the amount of water pollutants it carries. These can be included in the concept by calculating a substance-specific dilution volume that is necessary for diluting a pollutant concentration to a safe concentration. In contrast to the former ‘grey water footprint’ by Hoekstra et al. (2011), the calculation method has been adapted (Eq. 2-2).

In the third step, the quantitative water flows are regionalised by multiplying them with a basin-specific water stress indicator. As Available WAter REmaining (AWARE) by Boulay et al. (2018) is a widely accepted approach, it has been chosen here. The LCA characterisation factors are derived by comparing the basin-specific available water remaining with the consumption-weighted world average value (Schomberg et al., 2021), while the available water remaining is the hydrological water availability of a catchment area minus human water consumption and environmental water requirements. Characterisation factors are expressed in (m^2 * month) m^{-3}, which would be the surface-time equivalent required to generate one cubic metre of unused water (Boulay et al., 2018). Although it is theoretically possible to calculate characterisation factors for AWARE on a grid cell level (in accordance with Figure 2-3), these values would have little significance due to high uncertainties. An assessment on a basin level is a better choice. Together with the weighting by multiplication, the three quantitative water flows from Figure 2-3 can be summarised by the sub-indicator quantitative WSF (WSF_{quan}), while the qualitative WSF (WSF_{qual}) is the theoretically needed volume to dilute process-related aluminium emissions to water bodies to the level suggested by the drinking water standard of the World Health Organisation (WHO, 2018).

2.2.4 Application of the WSF in WANDEL

The challenge in performing a regionalised LCIA is the exact knowledge of all process locations. Only then can process water uses be assessed with the AWARE characterisation factor of the respective basin. In WANDEL, the locations of the case studies are known, and the supply chains of nine relevant mineral resources have been regionalised. Hereby, the most important countries of origin of aluminium, clay, coal, copper, iron, gypsum, lime, lithium and phosphate were identified based on the composition of the respective world market. For each country, corresponding mines were identified and grouped according to prevailing water stress and regional geology. For these mine clusters, life cycle inventories were prepared or expanded and added to the LCI. For all other processes along the supply chains, the analyses are based on the LCA database ecoinvent 3.5 (Wernet et al., 2016).

The WSF is determined for the construction and operation phases related to the production of 1 kWh of electricity as LCA, respectively. For the relation of the construction phase to 1 kWh, the lifetimes, annual electricity production and the share of facilities used to produce electricity were considered. The water use of each case study, as reported by the practice partners, was added to existing basic LCA models of the respective form of electricity generation. The LCIA was performed with the modified AWARE LCA implementation from Schomberg et al. (2021). These technical details also apply to the calculation of the indicators of the ESA, which is described in Section 2.1. The LCA models had been further modified with case study-specific data for this purpose. A detailed description of the LCA models for each of the case studies is given in Appendix A.

For the investigation of the case studies, the results of the WSF were considered in the form of a spatially explicit hotspot analysis as direct and indirect impacts (e.g. Figure 3-2). The hotspot analysis serves to identify the most important contributions for comparing the impacts of the single case studies. 'Direct' refers to on-site impacts at the location of the respective case study here, while 'indirect' impacts are located elsewhere, i.e. remotely, in relation to the location of a case study. For the hotspot analysis, the LCA of each WSF sub-indicator was analysed on the level of single process contributions. All processes along the supply chain that contribute more than 1% to the overall result of a WSF sub-indicator were included in the hotspot analysis. Each contribution of the processes was normalised with the median of all process contributions of all case studies to a normalised WSF sub-indicator. Contributions above 50 were counted as hotspots. The limit of 50 is an empirical value that enables the identification of comparable hotspots for very different case studies with results that span over several orders of magnitude. It represents a medium stress level on a scale from 0 to 100. This approach is described in detail by Schomberg et al. (2021).

The developed WSF concept was used to consistently compare the on-site and remote impacts of the construction and operation phases of the very different WANDEL case studies on water resources. In this way, it contributes to answering the WANDEL questions on the local and regional level, when it comes to the case studies, and on the global level, when it comes to global supply chains.

2.3 Ecosystem Service Indicators

Author: Martin Pusch

2.3.1 Introduction

This study aims to show the current impacts of hydro- and thermos-electrical production on water bodies, using the key concept of river ecosystems services. Specifically, we apply the methodology proposed by Burkhardt al. (2009) to assess river ecosystem services related to energy generation in two different European territorial contexts, i.e. Italy and Germany.

Thus, the specific goals of this study are as follows:

1) assess the effect of a hydroelectric power plant (run of the river) on ecosystem services of the Tiber river

2) evaluate the effect of a thermoelectric power plant on ecosystem services of the Danube river

3) analyse similarities and differences, in terms of ecosystem services provided and energy impact in a Mediterranean and a continental area.

2.3.2 River ecosystem services and water-energy nexus

Natural ecosystems always provide valuable goods and services to people (Daily, 1997; Yanmaz and Gunindi, 2003; Liang et al., 2015), and they have a crucial role in the provision of each component, i.e. food, water and energy, for human well-being (Costanza et al., 2014; Grizzetti et al., 2016; Karabulut et al., 2016). Holdren and Ehrlich (1974) first proposed the concept of 'ecosystem services (ES)', which are now defined as the benefits that humans derive from ecosystems (MEA, 2005; TEEB, 2010). Several studies (Costanza et al., 1997; MEA, 2005; TEEB, 2015) have been conducted to analyse and provide insights on these services and to investigate the connection between ecosystems, society and human well-being (Haines-Young and Potschin, 2013; Maes et al., 2013; Maes et al., 2014).

Water-related services have received increased attention, as water is vital to life and its value is easily appreciated by humans. Freshwaters were highlighted as an ecosystem that provides different services by the Millennium Ecosystem Assessment (MEA, 2005; Karabulut et al., 2016, Hornung al., 2019). In particular, riverine hydromorphological processes and functions have a pivotal role in shaping and maintaining river habitats and their ecological functions, which then provide various services to society (Carolli et al., 2018), including energy supply services.

Nowadays river ecosystems are subject to several pressures that affect their structure and functioning. Understanding how stressors interfere with the ecological status and the delivery of ecosystem services is essential for the development of effective river basin management plans, now and in the future (Halpern et al., 2008; Brown et al., 2013; Teichert et al., 2016). In particular, stressor interactions may have additive, synergetic or antagonistic effects on river ecosystems (Crain et al., 2008; Hering et al., 2015; Nõges et al., 2015; Piggott et al., 2015). In this regard, Hering et al. (2015) addressed multiple stressors for water resources in Europe, and Giakoumis and Voulvoulis (2018) incorporated ecosystem services as indicators of impacts for outlining a participatory framework for pressure prioritisation. They highlighted that diffuse pollution (45%) and hydromorphological degradation (40%) account for the most important pressures impacting European river systems (EEA, 2012a; ETC-ICM, 2012a; Hering et al., 2015). Both these impacts possess several individual components with complex interactions. Diffuse pollution mainly concerns increased nutrient loads and the resulting eutrophication, often associated with fine sediment and toxic substances. Hydromorphological degradation refers to water abstraction translated into low flows and morphological stress due to barriers, bank fixation, removal of riparian vegetation and the subsequent increase of water temperatures (ETC-ICM, 2012b). Consequently, water bodies are affected by a complex mix of stressors, and energy production is one of the main causes (Schinegger et al., 2012; Hering et al., 2015), as water is essential for almost all energy generation processes. Electrical power production is one of the largest water-intensive activities worldwide (IEA, 2018): it affects water resources through thermal and chemical pollution and requires massive withdrawals from our rivers, lakes and aquifers. Energy production's dependence on water availability makes it vulnerable to water scarcity (Mesfin et al., 2015); as a result, water is now a constraining factor for power plants across the globe (Rodriguez et al., 2018). This interdependence between water and energy is referred to as the water–energy nexus (Ackerman et al., 2013; Lubega et al., 2016). Growing global concern about this connection has led to an increase in the number of related studies in recent years (Scott et al., 2011; Hussey et al., 2012; Ackerman et al., 2013; Hamiche et al., 2016; Miglietta et al., 2018), whose goal is to ensure a sustainable supply of both. In this work, of the different energy production methods, we focus on the effects of thermal power and hydropower generation on rivers. Hydroelectric power plants strongly impact rivers, affecting the channel morphology, community structure, and functioning of stream ecosystems (Petts, 1984; Graf, 1999; Ward et al., 1999; Poff et al., 2007; Elosegi et al., 2010; Izagirre et al., 2013). While hydropower plants need river water to run the turbines, thermoelectric plants fueled by coal, fuel oil, gas, and uranium, use freshwater for cooling.

2.3.3 Thermal power plants

Thermoelectric power is a critical area of focus in the water–energy nexus. In 2005, thermoelectric production accounted for 41% of freshwater withdrawals in the United States (US), surpassing even agriculture (Kenny et al., 2005). In Europe in 2008, about 43% of the water withdrawals were used for thermal power plant cooling (EUREAU, 2009). This makes the thermal power plants in the US and Europe the largest water users in comparison with other sectors (Vassolo and Döll, 2005; Gjorgiev, 2017).

Cooling systems have been demonstrated to be the most water-consuming step of the thermoelectric generation process (Sovacool and Gilbert, 2014; Pan et al., 2018). Thermoelectric facilities boil water, creating steam to spin turbines that generate electricity: they obtain heat by burning fossil fuels that must be dissipated in cooling systems (Martin, 2019). In turn, different cooling types (i.e. wet or dry) require both different amounts of water and heat dissipation systems. The two most commonly applied methods for thermoelectric plant cooling are ‘re-circulating cooling’, which typically utilises evaporative cooling towers expelling the waste heat into the atmosphere and ‘once-through cooling’, where waste heat is transferred directly to rivers (Averyt et al., 2011). Both approaches rely on aquatic water availability (Brauman et al., 2007): once-through-cooling systems involve higher water withdrawals, while re-circulating cooling have higher water consumption volumes (Feeley et al., 2008).

Between the two cooling systems, re-circulating cooling towers withdraw lower volumes from the river, but evaporate considerably more water, thereby endangering fish habitat and other downstream river uses during low flow periods (Stewart et al., 2013). They have a negligible effect on river temperatures (Miara and Vorosmarty, 2013), causing, in some cases, a small net heat loss from the river systems and contributing to a reduction in average water temperatures. (Stewart et al., 2013). On the other hand, once-through systems lead to an increase in water temperature, usually limited by environmental law. In the European Union, water temperatures downstream from the point of discharge should not exceed 1.5 °C and 3 °C above natural temperatures (or 21.5 °C and 28 °C) in salmonid and cyprinid waters, respectively (European Parliament and Council of the European Union, 2006; Raptis et al., 2016). According to Logan et al. (2018), the size of the receiving waterway and the temperature difference between intake and discharge water are the largest factors that affect river conditions. The use of water by power plants can alter the natural characteristics of the receiving body through thermal pollution and water consumption with irretrievable losses in the atmosphere. (Stewart et al., 2013). River flow reduction, oxygen depletion, thermal shock and potentially limited water supplies downstream are likely to affect river ecosystem services downstream (Verones et al., 2010; Vorosmarty et al., 2010; Miara et al., 2013). Worldwide riverine thermal pollution patterns were investigated by Raptis et al. (2016) who identified several areas of high concern. Several pieces of evidence indicate that low flow and rising temperatures contribute to shifts in aquatic ecosystems (Schindler, 2001; Schindler et al., 2005; Caissie, 2006; Stewart et al., 2013), reducing the abundance and connectivity of suitable habitats (Rosa et al., 2012). Warmer areas along the river corridor, in fact, may provide refugia for cold-intolerant invasive species, further threatening native aquatic wildlife (Dukes and Mooney, 1999; Durance and Ormerod 2007; Morgan et al., 2003; Ormerod, 2007; Pandolfo et al., 2010; Rosa et al., 2012; Logan and Stillwell, 2017).

Other ecological impacts of thermal power plants are related to coal combustion, i.e. the release of emissions that adversely affect the aquatic, atmospheric environments and human health. Coal is known to contain multiple chemicals, carcinogens and heavy metals that can be mobilised through combustion, leading to contamination of habitats (Baba, 2003; Silici et al., 2013). In particular, ash from coal-fired thermal plants have been shown to contain several toxic elements, such as lead (Pb), zinc (Zn), cadmium (Cd), nickel (Ni) and cobalt (Co), which can leach out from ash and contaminate soil as well as groundwater and surface water (Davison et al., 1974; Klein et al., 1975; Campbell et al., 1978; Gehrs et al., 1979; Hansen and Fisher 1980; Hulett et al., 1980; Deborah and Ernest, 1981; Burcu et al., 1997; Rubin, 1999; Baba, 2000, 2000a, b).

The burning of coal, which is the most carbon-intensive fossil fuel, is a leading contributor to climate change. Coal-fired power plants have been proved to be the largest source of greenhouse gas emissions of the US, with approximately 2.125 billion metric tons of carbon that accounted for 81% of CO_2 emission in 2008 (EIA, 2009; Wilson et al., 2012). Recent climatic changes have increased the likelihood of heatwaves and droughts, which significantly impact the temperature and availability of river water (Schar et al., 2004; Dai et al., 2009; Gjorgiev, 2017). In this regard, Behrens et al. (2017) discussed the vulnerability of power generation to water scarcity and water temperature on a basin level, suggesting adaptation strategies for the European Union. (Lohrmann et al., 2019).

2.3.4 Hydropower plants

Hydroelectric development requires the construction of large structures to divert river flow through turbines. The impact of hydropower production on riverine ecosystems has been discussed for decades (Baxter, 1977; Rosenberg et al., 2000; Poff and Hart, 2002; Petts and Gurnell, 2005; Gupta et al., 2012; Lange et al., 2018). As suggested by Brismar (2002), a dam necessitates four main types of manipulation of the river flow regime: blockage, storage, regulation, and withdrawal of the river flow. These modifications also induce geomorphic and biological effects that reduce the potential to provide river ecosystem services and the consequent goods derived from humans (Grizzetti et al., 2016; Hornung al., 2019). There are three main types of hydroelectric power plants: storage, run-of-river, and pumped storage plants (Gulliver and Arndt, 1991; Novak et al., 1996). Among these, only a storage plant requires a large dam to regulate the flow in response to the electricity demand. In contrast, a run-of-river plant does not usually involve large dams and thus does not operate using intermittent releases (Brismar, 2002).

Hydropower plants are well known for causing profound effects on habitat provision by damming, reducing the flow in natural stream channels, and creating new water flow paths through man-made side canals (Kiplagat et al., 1999; Mwaura et al., 2002; Gunkel et al., 2003; Mwaura, 2006; Izagirre et al., 2013). Channel changes can lead to homogenisation in both river dynamics and biota (Poff et al., 1997; Poff et al., 2007; Vitule et al., 2012), including alterations of the river cross-section, bed material, slope, pattern, and bedforms (Bizzi et al., 2015). Specifically, dams function as barriers along the river continuum, which modify sediments, nutrient flows (Welcomme, 1985) pH, electrical conductivity and dissolved oxygen levels (Ward and Stanford, 1979; Kiplagat et al., 1999; Kemdirim, 2005; Mwaura, 2006). In particular, phosphorus and nitrogen are key nutrients for primary production in aquatic ecosystems (Thomas et al., 2001; Doyle et al., 2003), and changes in the concentrations and forms of these nutrients can result in altered nutrient limitation patterns of rivers (Petr, 1978; Hecky, 1988; Smith et al., 1999; Havens et al., 2003). Several studies have investigated the effect of hydroelectric power plants on river nutrient dynamics (Butturini and Sabater, 1998; Peterson et al., 2001; Martı et al., 2004). Discharge was found to be the main factor controlling nutrient uptake efficiency in rivers (Izagirre et al., 2013). In parallel with the amount of water diverted for power production, the availability of nitrogen and phosphorus decreased by 85% (Ideva et al., 2008).

Freshwater vertebrates have experienced severe declines in spatial distribution and abundance (Strayer and Dudgeon, 2010). One of the most important causes of this decline is habitat loss and fragmentation due to hydropower development (O'Hanley et al., 2020). Moreover, the construction of dams increases human activity, which is one of the major drivers of biological invasion (Gelbard and Belnap, 2003; MacIssac et al., 2004; Hulme, 2009). Non-native species invasion is facilitated by increasing the standing water area, which causes the replacement of lotic species by other lentic ones (Copp, 1990; Havel et al., 2005; Liew et al., 2016; Xiong et al., 2018). Sun et al. (2019), while analyzing habitat and fish species changes due to hydropower, highlighted that non-native fish gained significantly more habitats and that migratory fish richness decreased by 51% (O'Hanley et al., 2020). Thus, dams, as barriers, affect the life cycle of these species.

Regulation of river water temperature also plays a key role in the conservation of native species. Warm temperatures can can provide alien species with an establishment opportunity, enhancing their spread. Shi et al. (2019) found that hydroelectric power generation has induced a temperature increase in the hyporheic zone: the ecological transition area between surface water and groundwater systems that acts as a hotspot for biogeochemical processes. This is to be considered even in the light of global warming, which is leading to an inevitable increase in river water temperatures.

Dams are essential for several human activities related to water management. Their purposes range from water allocation for irrigation, flood risk mitigation to recreational activities (Bizzi et al., 2015). Dams constructed for hydroelectric purposes can at the same time contribute to mitigating flood risk through the regulation of the water flow (Sahin et al., 2016). Therefore, there is a positive correlation between hydropower plants and flood control. On the other hand, agriculture has a conflict of interest in the use of available water with energy production. Several studies (Fredrik, 2011; Hung, 2012; Pearse-Smith, 2012; Kuenzer et al., 2013; Hung et al., 2014a; Manh et al., 2014; Scherer and Pfister, 2016) conclude that hydropower developments upstream have negatively impacted the water regimes and sediment loads on the main river branches and floodplains downstream (Tran et al., 2018).

In addition to the natural ecosystem services just addressed, freshwater bodies provide a variety of cultural services, the most easily perceived by humans (Vermaat et al., 2015; Hutcheson et al., 2018). Some examples of these are swimming, fishing, sightseeing, environmental education, and other activities that allow people to enjoy river ecosystems' benefits. Having analysed the spatial characteristics of rivers at the landscape level, studies (Ward et al., 2002; Datry et al., 2016) underline that streamflow is of paramount importance in water services (Brauman et al., 2007). Water quantity is a decisive factor affecting the aesthetic and recreational functions of river ecosystems and their economic value (Lu et al., 2001; Pflüger et al., 2010). River landscape services have declined with increasing hydropower services due to the reduction in river flow, resulting in long-distance dehydration of river courses, which affects the quality of the river landscape (Fu et al., 2019). Dams, as a barrier for river continuity, also have a negative influence on various water-related activities such as rafting suitability and ship navigation. According to Jia et al. (2019), there is an inverse relationship between hydropower generation and downstream navigation capacity. In some cases, water released from large hydropower plants guarantees river navigability in dry months, while withdrawals for small hydropower plants may locally hinder the navigability (Carolli et al., 2016).

Finally, regarding the reduction of greenhouse gases, hydropower is known to be an important source of clean energy with low-carbon emission, thus representing an excellent alternative to fossil fuels (Steinhurst et al., 2012). It is currently the leading renewable energy source, contributing two-thirds of global electricity generation from all renewable sources combined. However, an analysis of data collection has revealed that average greenhouse gas emissions from hydropower are actually much higher than expected (Barros et al., 2011;

Scherer et al., 2016), and individual plant emissions can even exceed those of fossil fuel plants (Abril et al., 2005; Hertwich, 2013; Räsänen et al., 2017). As suggested by Ocko et al. (2019), short-term climate impacts of hydropower are much larger than their long-term ones, especially regarding new plant development. Therefore, these issues need to be investigated urgently because hydropower is expected to grow at least 45% by 2040 (Ocko et al., 2019), which could further threaten river ecosystem services.

2.3.5 Links between impacts and ecosystem services

In this context, the holistic DPSIR model is a good analytical framework for assessing water issues (Karageorgis et al., 2004; Kristensen, 2004; Skoulikidis, 2009), as it allows a better understanding of the complex link between the impacts on river ecosystems and their consequences on the services they provide (Kelble et al., 2013). Specifically, drivers (in our case hydro and thermal energy production) cause pressures (i.e. diffuse pollution, water abstraction and physical intrusions) and, as a result, affect the waterbody state (i.e. water quantity, ecological and chemical status). This has consequences on ecosystem functioning (i.e. changes in river morphology, hydraulics and flow regime, sediment continuity, physical habitats and biotic communities) and thereby on ecosystem services (i.e. habitat provision for biodiversity, temperature regulation, self-purification and water-related activities), which may require a policy response (i.e. water use restrictions, water-saving devices, alternative supplies and restorative actions). Therefore, ecosystem-based management should focus upon ecosystem services that recognise the multi-functionality of the water systems and, at the same time, account for the benefits and values associated with human well-being (Haines-Young and Potschin, 2010; Kelble et al., 2013; Hering et al., 2015).

To support decision-making aiming at such ecosystem-based management, we summarised the effects of thermoelectric and hydroelectric power plants on the various ecosystem services (Table 2-1).

Table 2-1: Overview of the effects of thermoelectric and hydroelectric power plants on various ecosystem services (arranged by ecosystem service main group, subgroup and types.

Main ES group	Subgroup	Ecosystem service	Effects by power plants	
			thermo-electric	hydro-electric
Provisioning	Nutrition	Cultivated crops		X
		Plant resources for agricultural use		X
		Wild animals and fish	X	X
		Surface water for drinking		X
		Ground water for drinking		X
	Resources	Fibers and other plant materials for direct use or processing		X
		Water for non-drinking purposes	X	
	Biomass-based energy resources	Plant-based resources		X
Regulating	Retention (Self-purification)	Retention of organic C		X
		Retention of N		X
		Retention of P		X
	Global climate regulation	Retention of greenhouse gas emission / carbon fixation	X	X
	Extreme discharge mediation	Flood risk regulation		X
		Drought risk regulation		
	Sediments	Mass flow / Sediment regulation		X
		Soil formation in floodplains		X
	local climate regulation	Local temperature regulation/Cooling	X	
	Habitat	Maintaining habitats	X	X
Cultural	Cultural	Landscape aesthetics	X	X
		Natural and cultural heritage		X
		Unspecific interactions with the riverine ecosystem	X	X
		Education and science		X
		Water-related activities	X	X

2.4 Water and Energy Security Indicators

Author: Tobias Landwehr

Energy and water are coupled via various direct and indirect means (Hamiche et al., 2016). Water is used as a coolant in Rankine cycle processes (Winterbone and Turan, 2015), a driving force in hydropower plants (Zarfl et al., 2015) and a prerequisite for biomass-based energy systems (Jans et al., 2018; Flörke et al., 2018). Likewise, global electrical energy generation has increased tremendously. In 2017, it quadrupled compared to the level in 1971 (International Energy Agency, 2019). The energy demand and water dependency of electrical energy are thus larger than ever.

Surprisingly, assessment systems that provide insights into the manifold interconnections between energy generation and water availability are rather scant. The only known energy–water assessment system is the Water for Energy Framework (W4EF) by the World Water Forum (Lemoine and Bellet, 2015), which, however, has shortcomings regarding governmental aspects (Pahl-Wostl, 2015; Daniell and Kay, 2017), economic and capacity restrictions (Rhoades, 1995; Rogers et al., 2002), long-distance and long-term effects (Zarfl et al., 2015; Grill et al., 2015) as well as scaling (Abbott et al., 2019; Platzer et al., 2016). A new, holistic assessment system was thus needed.

WANDEL established a new holistic assessment system with six main indicators to assess the energy–water dependency and to evaluate whether the actual and projected energy generation is secure with respect to water supply. The main indicators, alongside their main scientific sources, are thus as follows:

1. Competition for Water (Rhoades, 1995; Solow, 2008; Hunt, 2011): Electric energy generation is not the only sector that consumes more or less limited water resources; the domestic, environmental, industrial and agricultural ones also do. The main indicator demonstrates how far this competition for water endangers the security of electricity generation via an assessment of sector competition and population development.
2. Constraints on Water (van Vliet et al., 2013; Flörke et al., 2018): Water as a resource is vulnerable to varying anthropogenically and environmentally induced characteristics, especially temperature or quantity. These constrain the resource and thus potentially limits electricity generation, which is reflected by the indicator in its assessment of the temperature and quantity of various water sources of the region.
3. Dependencies on Water (International Energy Agency, 2018; Bolognesi et al., 2014): The degree of a region's continuously water-dependent electricity generation might endanger its generation security due to common 'week point' of the dependencies, which the indicator demonstrates via direct dependencies and a region's economic–technical capacity to escape this dependency.
4. Water Footprint (Hoekstra, 2017; Schomberg et al., 2021): Resources for electricity

generation do have origins in faraway regions, where their extraction and export endanger water security. The indicator assesses the impact on faraway water resources of both the resources necessary for the erection of power plants and the resources for their continuous operation (e.g. coal or uranium).

5. Feedback Effects (Grill et al., 2015; Kedra and Wiejaczka, 2018): Large-scale infrastructures such as power plants or dams influence the nature of their water resources (most often riverine systems) tremendously. The indicator reflects this by assessing both the fragmentation of riverine systems as well as the effect on the disturbed sediment balance, which are indicators of ecologic, economic and agrisocial impacts.
6. Institutional Capacity (Pahl-Wostl, 2015; Van de Graaf and Colgan, 2016): The governing of the water–energy dependency is a complex administrative jurisdictive process. The indicator reflects this by assessing the governance capacity of and corruption impact within a country as well as the administrative and legislative situation of a surveyed region.

The indicator system is designed in such a way that it applies to both (sub-)basin regions (e.g. the Nile) or administrative regions (e.g. Bavaria).

Each of the main indicators is backed by several carefully selected sub-indicators and sub-indicator assessment methodologies (Figure 2-4). They can be examined, e.g. 'Fragmentation Stress' of 'Feedback Effects' is derived from the Dam Impact Matrix from Grill et al. (2015), whilst 'Intersectoral Competition' from 'Competition on Water' evaluates regional sector water consumption shares based on a modified Herfindahl-Hirschman-Equation assessment.

Each sub-indicator receives a score from one (the best) to five (the lowest) and is evaluated by highly individual processes. The scores are treated arithmetically to generate the final main indicator score.

To illustrate, the main indicator 'Competition for Water' for the Southern Region of Nevada, USA, including the desert city Las Vegas suggests that the population growth has been increasing rapidly, with limited inner water supply from the region itself (Foresta, 2018). This produces a high-risk situation for the future, reflected by the sub-indicator 'Demographic Demand'. Let's suppose a 4.0 rating for this.

Furthermore, the water-consuming sectors (including electricity generation) are almost monopolistically dominated by one specific sector – namely the domestic sector (Foresta, 2018). Its consumption quantity substantially exceeds the others – and this in a water scarcity situation. This means that small changes in the domestic water consumption could (nearly) deplete its scarce water resources and thus endanger the security of all other sectors (including electricity). The 'Inter-Sectoral Competition' sub-indicator reflects this. Therefore, let's give this a 5.0 rating. So, the arithmetic mean of both sub-indicators would form a very alarming 4.5 for the main indicator 'Competition for Water'.

Furthermore, 'Demographic Demand' assesses the population growth trend as a metre for the overall consumption direction of a region. It differs from 'Inter-Sectoral Competition', which measures a monopoly pressure situation of water consumption, which could be of agricultural or industrial origin. (Further definitions and detailed descriptions of the sub-indicators can be obtained from Landwehr et al. (submitted).

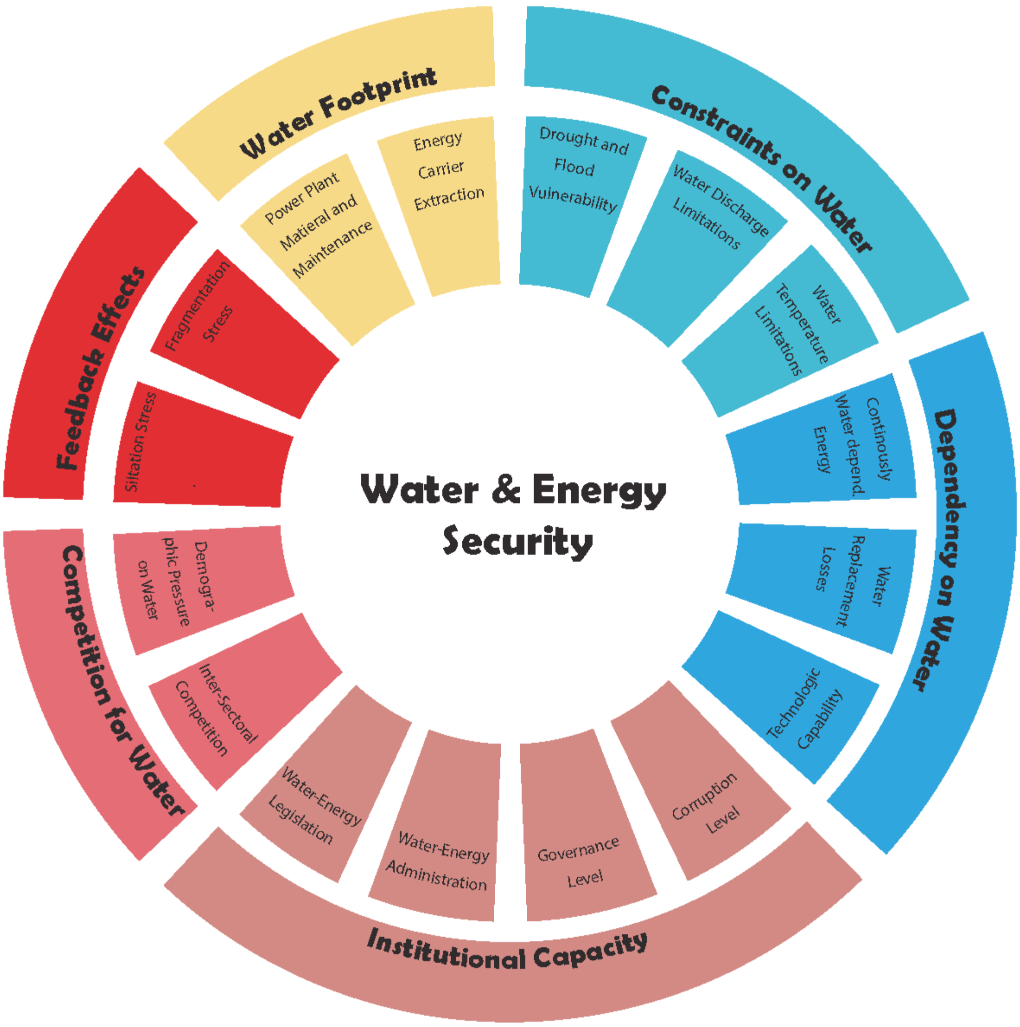

Figure 2-4: Overview of the energy-water indicator system. Each main indicator (outer circle) expresses a high impact topic in the energy-water relationship, which it will rate. The main indicators' ratings are formed by the arithmetic mean of their respective sub-indicators (inner circle). The sub-indicators are rated by complex, individual rating mechanisms of topics that reflect the central characteristics of their overarching main indicator.

2.5 Risk Methodology

Authors: Jazmin Campos Zeballos, Liliana Narvaez, Zita Sebesvari

In the context of the WANDEL project, UNU-ESH aimed to understand the water-energy nexus in the bioenergy case study: 'Electricity generation based on sugarcane bagasse in Rio dos Patos, Goiás, Brazil', with reference to land-use scenarios and technology improvement (see Section 3.4).

The risk assessment was in line with the Intergovernmental Panel on Climate Change (IPCC) risk framework (IPCC, 2014) with few changes in the approach for incorporating the technological phase in the assessment. The framework was applied to understand how droughts would affect a bioenergy system and to identify which and where were the weak and the strong components.

Due to the novelty of a risk assessment applied to energy systems, the subcomponents and their analysis were tailored to the case study and the environmental context. Sugarcane bioenergy systems have internal feedback loops that can further increase their resilience to climate change. For instance, the recovery of sugarcane water for further use in industrial processes and water recirculation within the mill makes the industrial subsystem almost closed. Or the use of industrial wastewater and vinasse to irrigate sugarcane reduces its impact on water resources, reduces freshwater demand for irrigation, and increases sugarcane crop yield.

The risk assessment was applied to the agricultural and the industrial subsystems of the sugarcane bioenergy system. It included hazard, exposure and vulnerability assessments adapted to and considering both subsystems. The most noticeable adjustment was on the vulnerability assessment, commonly assessed under a socio-ecological approach. As an energy system has strong technological components that must be included to understand the system's vulnerability, some authors have been working towards the use of a social-ecological-technological approach in which the technological sphere is included in the assessment to have a complete overview and understanding of the system (Ahlborg et al., 2019; Krumme, 2016; Markolf et al., 2018; van der Leer et al., 2018) (for more details on the case study, read (Narvaez Marulanda et al., 2021[manuscript in preparation])).

The analysis was performed yearly from 2000 to 2014 and included only local impacts in the basin. The analysis excluded economic and market impacts in the system and changes in governmental initiatives to promote sugarcane.

This subchapter aims to provide the necessary steps to fill and understand the elements within the risk framework applied to an energy system using, as an example, a sugarcane bagasse-based electricity generation system (see **Figure 2-5**).

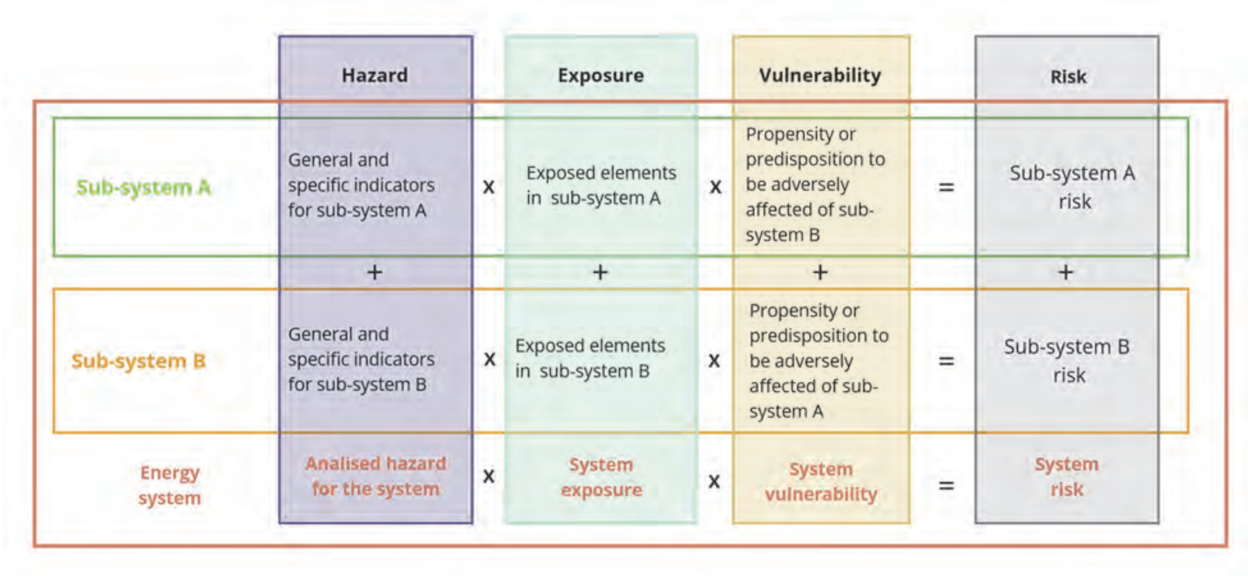

Figure 2-5: Risk Framework

2.5.1 First step: Energy system definition and geographic extension

An energy system has different components that can be organised into subsystems. **Figure 2-6** shows two subsystems; however, depending on the energy system, it can have more. Questions that can help identify the subsystems are as follows: Where is the energy plant located? Which materials and resources are used as input for the system to generate energy? From where are these materials and resources sourced?

The energy plant is considered a subsystem, with the material and resources used to generate energy coming from other subsystems. A bioenergy system will have two sub-components, agriculture from which raw material is sourced to generate energy, and the industrial phase in which the raw material is transformed to energy (see **Figure 2-6**).

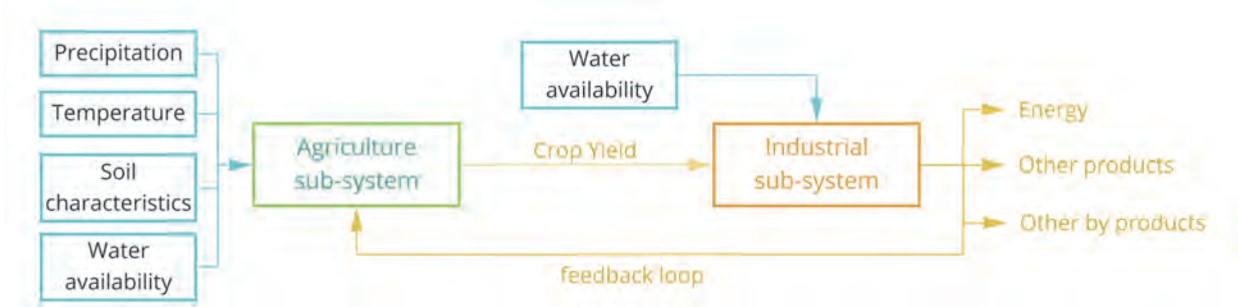

Figure 2-6: Bioenergy system

The geographic unit for analysing the risk of water-related hazards is a basin; therefore, for the system to function, the assessment's geographical scale is based on the basins involved. In the case study, both subsystems were located in the same basin; thus the assessment's geographical scope was one basin, Rio dos Patos.

Once the subsystems are identified and the geographic area defined, the optimal climatological conditions, soil characteristics, and water availability that are needed for the system to function can be listed.

For example, in the agricultural subsystem, the crop will grow healthy under certain precipitation patterns, temperature ranges, soil characteristics that can be achieved by soil correction and the minimum river water needed for irrigation. Subsystems related to natural resources should also include the land use cover in the basin, protected areas and compliance with the regulations regarding them, given that the health of the basin will influence the crop's health.

Usually, there is a time step between the agricultural and the industrial systems, which differs from crop to crop and should be considered during the risk assessment. The crop life cycle should be used as a year reference, as it will be the system calendar for plantation, harvest and energy generation.

The analysis should acknowledge other users in the basin to understand the water demand in the basin throughout the year. It is important to understand different users' behaviour and priorities during natural hazards, as changes in the water input, regulated by the soil type and land cover, will determine the water available for the different users in different months of the year.

Figure 2-7 summarises the relevant users to consider when the assessment is carried out.

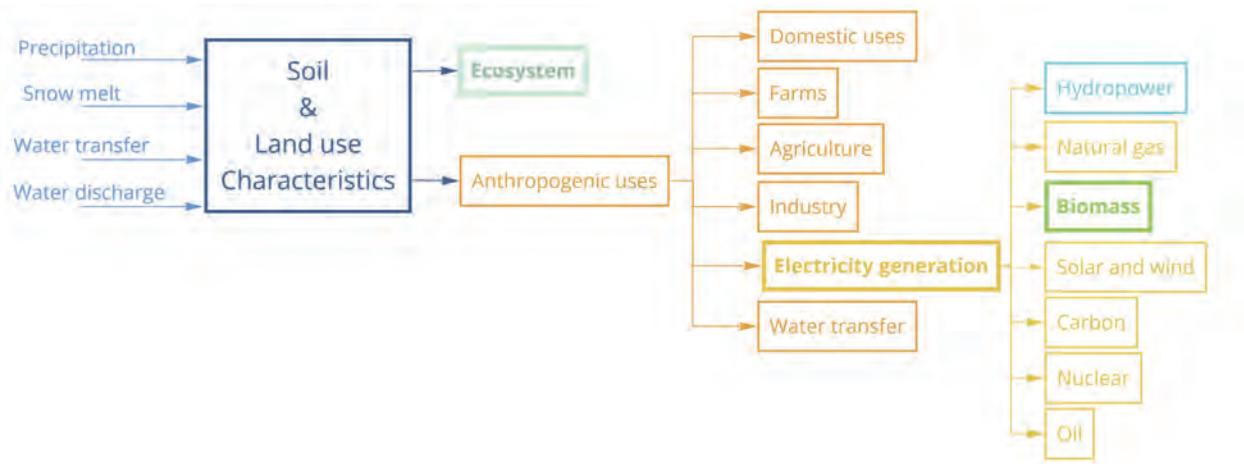

Figure 2-7: Basin users

2.5.2 Second step: Relevant stakeholders and data acquisition

After defining the system under analysis, its components and the basins involved, relevant stakeholders can be identified. Questions that can help to identify key stakeholders are as follows: Who is the authority granting water use permits? Who is the authority dealing with environmental permits and land-use changes? Is any research institution exploring or analysing the energy system or subsystems? Is any private or public association promoting this particular energy source?

Stakeholders are important for thoroughly understanding the system and the loops within it. They provide insights into the system from different points of view, identifying the data required, interpreting the results, and implementing adaptation measures. They manage the information and databases and can provide data and information for the analysis.

The stakeholders were selected to cover the basin analysis in general and the bioenergy system in particular. Figure 2-8 shows the basin and the stakeholders per component that should be considered. To have a comprehensive analysis, it is important to consider all levels of stakeholders.

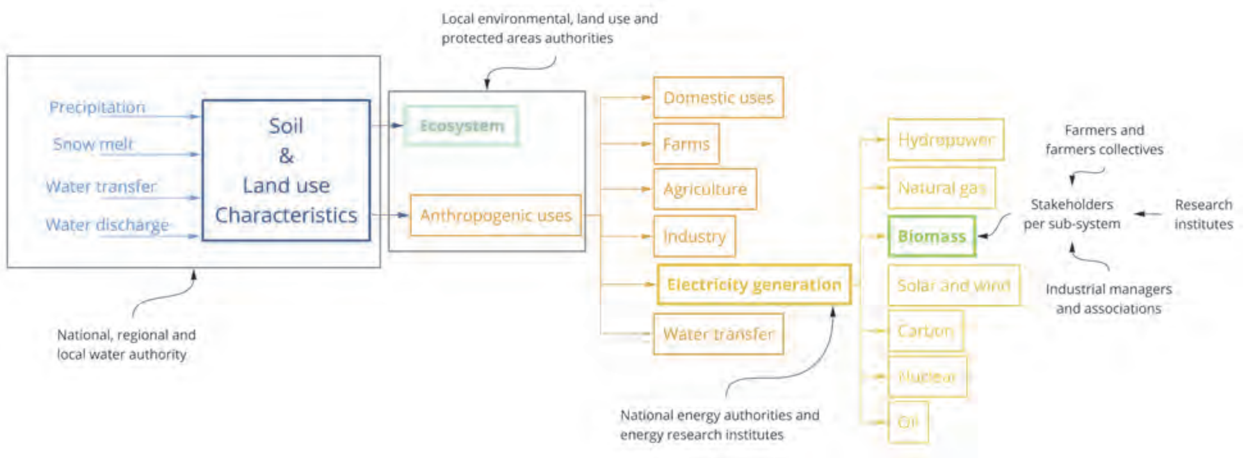

Figure 2-8: Relevant stakeholders

Therefore, the relevant stakeholders were thus identified, proceeding from a wide and general scope to a more specific lens.

- National and regional water authorities provide insights on water regulation for the basin regarding allocation and quality.
- Local authorities have a more intimate understanding of the basin, its users and their water demand, most likely land-use changes, and the basin's environmental status. Usually, the authorities are in charge of licensing, monitoring and controlling water use and land-use changes permits and controlling and monitoring water quality.
- National energy authorities manage and monitor the national energy agenda. Priority sources are promoted through it,. It often has a department or is connected to an energy research institute that analyses changes in the energy matrix and likely energy outlooks.
- The most important stakeholders are the ones related directly to the energy system. Research institutes should always be considered due to their specific knowledge of the subsystems and the system's general overlook and their extensive geographic scope. In Brazil's sugarcane case, Empraba Cerrados was a relevant stakeholder and partner of the project, which helped connect dots between the energy system in the basin and regional and national regulations and plans. In this particular case

of a bioenergy system, farmers and farmers' collectives gave a rich insight into the agriculture system and the raw material for energy generation. Moreover, mill owners, mill managers and industrial associations contributed with helpful insights on the industrial subsystem, loops within the industrial system design, and improvements in the system.

2.5.3 Third step: Hazard analysis

Hazard Indicators

Hazard is understood as 'climate-related physical events or trends or their physical impacts' (IPCC, 2014). Each hazard has unique indicators that can be found in the literature. In the case of drought, the most common are the Standard Precipitation Index (SPI), the Standardised Precipitation-Evapotranspiration Index (SPEI) and the Palmer Drought Severity Index (PDSI), among others.

Energy systems have specific water requirements for their subsystems that should be fulfilled for the system to function. They are also located in areas with specific climatological characteristics and prone to different hazards.

In bioenergy systems, the assessment is concentrated on a particular type of crop, in a basin with specific climatological characteristics, land use, and identified water users. Given the specific applicability of the analysis, on top of the typical indicators, indicators related to rain distribution, agriculture planning, temperature, and river and ecological flow, specifically for crops, can be added.

For example, rainfed and irrigated crops will depend on the region's precipitation pattern and temperature. If the precipitation volume is roughly the same every year, but its concentration in time changes and the rainy season's time frame shrinks, the crops will be affected, and the irrigation patterns will need to be adjusted. Additionally, analysing the length of the dry season and the consecutive days with less than a certain volume of precipitation in the rainy season can also be considered for identifying drought events for specific crops.

Hydrological patterns, including the ecological component, are also relevant for hazard analysis. It is important to acknowledge the ecosystem as a user in the basin when minimum flows are analysed. If national and local regulations establish an ecological flow threshold, it can be used as a reference; otherwise, the ecological flow can be defined depending on the biome, weather patterns, and historical flow data.

The hazard indicator for the industrial system is related to its water demand. It should be analysed considering other water users in the basin and water damming. When a drought occurs, usually water allocation is prioritised for the population and cattle, if there is no regulation to prioritise other users. The prioritisation of other users depends on the basin, local economy and national regulations.

In the case of sugarcane and the mill, sugarcane will be a priority over other crops to ensure its sprout. In this sense, only sugarcane recently planted can be irrigated before other crops during a drought event. The industrial demand is not a priority for water allocation in the region; for that reason, access to a dam to cover its water demand is key during a drought event.

It is relevant to do a monthly step analysis to identify months with higher risk. Different users' behaviour and water demand during those months in both drought and flood events will be meaningful when planning adaptation measures. The final result for the hazard assessment can be a single yearly value.

Hazard indicators' thresholds

Once the indicators are chosen, thresholds should be settled considering the subsystem management, weather patterns and ecosystem demand. Common indicators such as the SPI and the SPEI have thresholds that can be applied. In the case of bioenergy systems, in general, crops will have specific thresholds for identifying when it has been exposed to drought events. The region that was studied has thresholds too, which were used for the analysis. Similarly, the region has established thresholds for river and ecological flows, which were used in the assessment.

For other indicators, thresholds can be defined using the average of the historical data, natural breakings, standard deviation, or quartiles, among other statistics, to analyse historical data behaviour.

When it comes to bioenergy systems and specifically to sugarcane, farmers and mill managers, researchers use the quartile one as the threshold for weather patterns. They tend to plan the harvest year based on historical data, considering what 'has happened the most'. For this reason, in the case study, to define the different levels of drought, the thresholds were identified using quartile 1 and the standard deviation.

Hazard value

Risk assessments usually use values from 0 to 1, one being the strongest hazard event, most exposed system or most vulnerable component. In this sense, the final hazard value should be normalised to fit into the overall assessment.

The final value depends on the indicators selected and if they were grouped and weighted. If the indicators are to be weighted, stakeholders should be involved in the processes to ensure the inclusion of all perspectives.

2.5.4 Fourth step: Exposure analysis

Exposure is understood as 'the presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets' in the system that could be affected (IPCC, 2014). In this sense, exposed elements are elements within the energy system that a hazard can impact. For an energy system, it will be the energy plant, plus all elements in the subsystems that make the system work. Particularly for a bioenergy system, the exposed components are the crop that will be processed to produce energy and the mill's installed potential. Basic exposure data are land use, protected areas and maps of water bodies. Satellite images can be processed to identify the crop areas; however, it is necessary to have extensive knowledge of the crop characteristics to identify and classify them correctly.

Land use maps, protected areas and slopes can indicate where in the basin the crop might and can expand without jeopardising natural coverage key for maintaining the basin equilibrium.

The exposure of the crop can be the percentage of the geographical area covered by it. It is important to mention that when applied to future scenarios, the exposure should never be 100% or 1. This is because protected areas must be respected, and other crops and land uses may also expand.

The industrial exposure is the percentage of the installed potential the mill represents in the geographic unit. If it is the only mill in the geographic region, then it will be 100%. For future scenarios, the installed potential may increase with the crop area expansion. It depends on the national agenda and the priority role the analysed energy system plays in it.

2.5.5 Fifth step: Vulnerability assessment

The vulnerability of the energy system's exposed elements is understood as 'the propensity or predisposition to be adversely affected' (IPCC, 2014). It applies to the agricultural and the industrial subsystems and to the defined geographic extension in a bioenergy system.

In the case of sugarcane, it was applied to the mill in the basin, farmers within the basin, and farmers collaborating with the analysed mill close to the basin but outside its boundaries.

As a first step, relevant indicators for both subsystems were searched for in the literature. The industrial system's vulnerability is related to its performance and efficiency in water use and electricity generation. the electricity generated per cubic metre of freshwater extracted and the energy compromised per cubic me-ter that is not available in the basin are common indicators for energy systems when they are evaluated to understand their performance.

For the agricultural subsystem, the literature review aimed to identify indicators used to evaluate the vulnerability of the social, agriculture and soil, network infrastructure, environmental, economic, and governance components, which are key for the agricultural system's performance.

A semi-structured questionnaire was designed to cover the six components. The questionnaire collected data and information for each indicator to understand the adaptive and coping capacity, social susceptibility and ecosystem susceptibility and robustness.

In this sense, the vulnerability assessment considers relevant components or spheres of the agricultural subsystem such as governance and translates them into vulnerability elements.

After the indicators were reorganised into the vulnerability elements, statistics were applied to get numbers between 0 and 1, one being the most vulnerable.

The questionnaire contained the following: 1) yes/no questions, which had a value of 0 or 1 depending on what they were referring to; 2) questions with five different options, with each option having a value from 1 to 5 – these were settled with experts and later normalised to 1; 3) open questions in relation to quantities and percentages that were also normalised to 1 and 4) open questions aiming at description and information used to understand the context and farmers' perceptions of the bioenergy system and drought events.

Indicators and elements can be weighted according to experts' opinions. In the case study, the indicators and elements were not. The statistics behind the analysis of indicators per element differ, depending on the indicator and the information they contain. In general, the most common element value is the average of the indicators in it.

The final vulnerability value was the average of both subsystems due to the similarity of both values. However, it is important to be careful in this final step, as the value should represent both subsystems.

2.5.6 Final risk assessment value

The drought risk of the energy system evaluation is the sum of the system's hazard, exposure, and vulnerability values (see **Figure 2-9**). The analysis should include the most common indicators triggering alerts for drought events based on the hazard indicators, the most exposed elements, and where the vulnerability is coming from.

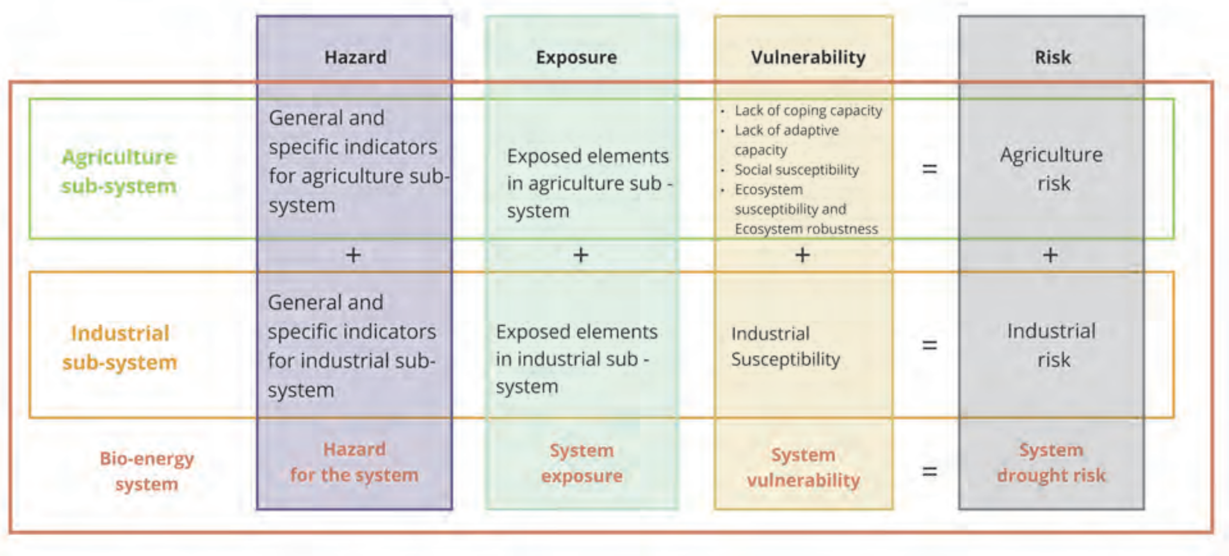

Figure 2-9: Drought risk framework for sugarcane-based electricity generation

2.6 WANDEL-Share

Author: Hinrich Paulsen

WANDEL-Share is a geoportal that was developed with the aim of facilitating easy management and analysis of geo- and Earth observation data in the project context. It was made available to all case studies with data supporting, e.g. the quantification of water scarcity footprints and is intended for practical applications after the end of the project.

WANDEL-Share, available at https://WANDEL.mundialis.de for invited users, features the following sections, which will be detailed in the following paragraphs:

- administration of users, applications and geodata
- user interface for geodata and geoprocessing (client)
- document management system

2.6.1 Administration of users, geodata and applications

WANDEL-Share has been built using free and open source Software (FOSS), utilising international standards from the International Organisation for Standardisation (ISO), the World Wide Web Consortium (W3C) and the Open Geospatial Consortium (OGC) to facilitate global interoperability. It contains a cloud-based geo-processing engine called actinia[1] (https://actinia.mundialis.de/) that facilitates the dynamic processing of satellite imagery, provided for free by the Copernicus Programme of the European Union.

As WANDEL-Share is global in scope, it was programmed as a web-based application with the possibility of self-registration and subsequent login. The self-registration was deactivated during the project lifetime for safety reasons but can be activated at any time. After login, the user sees the administration backend where they can, among other activities, request rights to applications and data. The so-called super-admin is able to grant sub-admin, editor and user rights that allow or disallow certain actions such as create, read, update and delete (CRUD). The meticulous implementation of user rights and roles, also extended into individual data layers, is important for future users, as it guarantees ownership and thus data privacy by design and not only superficially.

The administration backend also allows the upload of vector and raster data. As WANDEL-Share can also be thought of as a node in a Spatial Data Infrastructure (SDI), data can also be registered as a Web Mapping Service (WMS), which only stores the reference to a remote data repository. To exemplify data that was integrated by mundialis into WANDEL-Share to provide users with certain base data to start, their work can be grouped as follows:

- **Administrative**, covering administrative and research site boundaries

[1] https://github.com/mundialis/actinia_core

- **Eco regions**, covering global physical regions, land cover types and soils
- **Energy**, covering global power lines and networks, wind-power stations and photovoltaic power potential
- **Surface water**, covering world rivers and lake basins
- **Groundwater**, covering groundwater resources and recharge, areas of saline groundwater and global groundwater vulnerability to floods and droughts
- **Climatology**, covering global wind atlas, precipitation and temperature
- **SDG Indicators**, covering the proportion of the population using safely managed sanitation services and world population
- **Background layers**, containing a base map

The interactive nature of WANDEL-Share allows users to upload their own data or register data of interest from remote sources.

The ability to create so-called applications sets WANDEL-Share apart from most geoportals. An application is a Web-GIS client with an individual spatial extent, individual GIS tools and individual data. There is no limit to the number of applications that can be created and to do this no programming skills are required. The image below (Figure 2-10) depicts the user interface needed to configure an application.

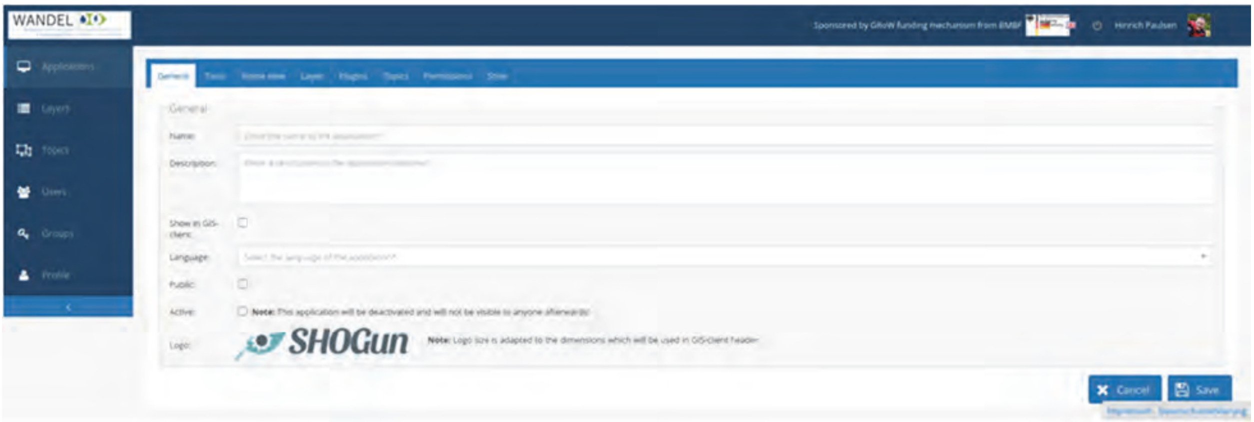

Figure 2-10: Configuring individual applications in WANDEL-Share

In the WANDEL project, each case study received an application, which enabled users to focus on data and the research question for their area of interest. At the same time, access to data from other case studies or areas was also possible because all data resides in the same repository and the data format follows international standards. The tool was developed keeping in mind interoperability across institutional and state boundaries and provision of easy service to future customers.

2.6.2 User interface for geodata and geoprocessing (client)

Data uploaded or registered in WANDEL-Share can easily be added to an application by dragging and dropping it to the right location in the layer tree which can be individually configured for each application. Data can be viewed in its spatial context, objects in the data can be searched for and its metadata can be queried. In addition, the client features the following functionality:

- Printing map content in widely used formats
- Measuring distances and areas
- Drawing points, lines, polygons, circles, rectangles, text and post-its through the annotation tool;
- Interactive loading of WMS such as https://ows.terrestris.de/osm/service?SERVICE=WMS&VERSION=1.1.1&REQUEST=GetCapabilities
- Starting of Sentinel-1 and Sentinel-2 processing chains

Besides more or less static data already present in WANDEL-Share the ability to dynamically process raster data originating from the Copernicus Programme of the European Union (EU) is another feature that sets WANDEL-Share apart from other geoportals.

To achieve this processing ability, the REST API of the FOSS GRASS GIS (https://grass.osgeo.org/) was utilised to access the approximately 400 functions available in the software via the internet. GRASS GIS was modified to be cloud-enabled (Neteler et al., 2012), meaning that computing processes can be dynamically allocated to several compute nodes. The resulting cloud computing engine is called actinia (Neteler et al., 2019), and the general computing workflow is depicted in the image below (Figure 2-11).

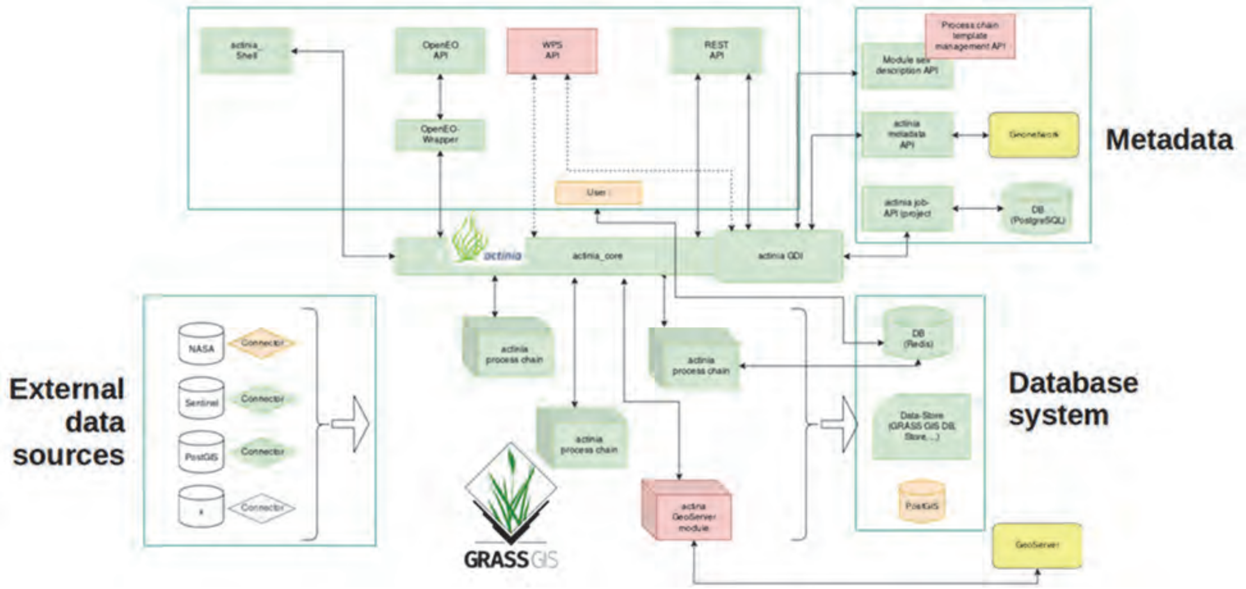

Figure 2-11: Actinia schematic

The following items are signature functionalities of actinia:

- Virtual machine (VM) configurations (CPU, RAM, memory, etc.) can be created, stored, modified and deleted (CRUD → create, read, update, delete).
- Configurations for the software to be installed in the VMs can be stored.
- An application programming interface (API) has been programmed that can be used to automatically order, start, configure, switch off and delete VMs. The advantage of this approach is the minimisation of cloud costs because VMs are ordered and operated only when in use and thus incur costs only then.

Regarding the dynamic processing of satellite images, radar and optical data from the Copernicus Program are accessible.

In WANDEL-Share, radar data of the satellites Sentinel-1a and 1b and optical data from the satellites Sentinel-2a and 2b can be processed utilising actinia. This is an automated process chain, where the desired area is marked on the map, a dynamic search for existing data in the desired period and adjustable criteria (RADAR: orbit direction, polarisation, product type and sensor operation; OPTICAL: time range and cloud coverage) is performed, following which an index calculation is carried out. The result of the calculation is immediately displayed in the map and the layer tree.

2.6.3 The Document Management System (DMS)

WANDEL-Share also features a so-called Document Management System, where the user can interactively create a structure of a document, i. e. a table of contents, and then populate the individual chapters with text, maps, graphs, pictures, etc. Individual elements, the nodes, of the structure can be created, modified and deleted at any time.

Overall, WANDEL-Share stands out because it was developed using FOSS, allowing for the adoption of ownership. At the same time, a lot of complexity was hidden behind user interfaces that allow the individual configuration of spatial data management functionality without the need to program a single line of code. Last but not the least, the geo-processing engine actinia is a very powerful tool when it comes to the analysis of Earth observation data and can be adapted to individual needs because all underlying source code is accessible.

2.7 References Chapter 2

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

Abril, G., Guérin, F., Richard, S., Delmas, R., Galy-Lacaux, C., Gosse, P., Tremblay, A., Varfalvy, L., Dos Santos, M. A., & Matvienko, B. (2005). Carbon dioxide and methane emissions and the carbon budget of a 10-year old tropical reservoir (Petit Saut, French Guiana). *Global Biogeochemical Cycles*, *19*(4). https://doi.org/10.1029/2005GB002457

Ackerman, F., & Fisher, J. (2013). Is there a water–energy nexus in electricity generation? Long-term scenarios for the western United States. *Energy Policy*, *59*(C), 235–241.

Alcamo, J., Döll, P., Heinrichs, T., Kaspar, F., Lehner, B., Rösch, T., & Siebert, S. (2003). Global estimates of water withdrawals and availability under current and future “business-as-usual” conditions. *Hydrological Sciences Journal*, *48*(3), 339–348. https://doi.org/10.1623/hysj.48.3.339.45278

Alcamo, J., Flörke, M., & Märker, M. (2007). Future long-term changes in global water resources driven by socio-economic and climatic changes. *Hydrological Sciences Journal*, *52*(2), 247–275. https://doi.org/10.1623/hysj.52.2.247

ANA. (2013). *Base Hidrográfica Ottocodificada Multiescalas 2013: Rios.* Agência Nacional de Águas.

Averyt, K., Huber-Lee, A., Macknick, J., Madden, N., & Tellinghuisen S. (2011). *Freshwater Use by US Power Plants: A Report of the Energy and Water in a Warming World Initiative.*

Baba, A. Leaching Characteristics of Solid Wastes from Yatagan (Mugla-Turkey) Thermal Power Plant. In D. O. O., I. Ozgenc, & Sozbilir H. (Eds.), *International Earth Sciences Colloquium on the Aegean Region IESCA – 2000* (pp. 83–88).

Baba, A. (2000). *Investigation of Environmental Geology of the Yatagan (Mugla-Turkey) Thermal Power Plant Waste* [Ph.D. Thesis], Izmir.

Baba, A. (2000). Leaching characteristics of wastes from Kemerkoy (Mugla-Turkey) Power Plant. *Global Nest: Int. J*, *2*(1), 51–57.

Baba, A. (2003). Geochemical Assessment of Environmental Effects of Ash from Yatagan (Mugla-Turkey) Thermal Power Plant. *Water, Air, and Soil Pollution*, *144*(1), 3–18. https://doi.org/10.1023/A:1022901924430

Barros, N., Cole, J. J., Tranvik, L. J., Prairie, Y. T., Bastviken, D., Huszar, V. L. M., del Giorgio, P., & Roland, F. (2011). Carbon emission from hydroelectric reservoirs linked to reservoir age and latitude. *Nature Geoscience*, *4*(9), 593–596. https://doi.org/10.1038/ngeo1211

Baxter, R. M. (1977). Environmental Effects of Dams and Impoundments. *Annual Review of Ecology and Systematics*, *8*(1), 255–283. https://doi.org/10.1146/annurev.es.08.110177.001351

Behrens, P., van Vliet, M. T. H., Nanninga, T., Walsh, B., & Rodrigues, J. F. D. (2017). Climate change and the vulnerability of electricity generation to water stress in the European Union. *Nature Energy*, *2*(8), 1–7. https://doi.org/10.1038/nenergy.2017.114

Berger, M., van, d. E. R., Eisner, S., Bach, V., & Finkbeiner, M. (2014). Water accounting and vulnerability evaluation (WAVE): considering atmospheric evaporation recycling and the risk of freshwater depletion in water footprinting. *Environmental Science & Technology*, *48*(8). https://doi.org/10.1021/es404994t

Bizzi, S., Dinh, Q., Bernardi, D., Denaro, S., Schippa, L., & Soncini-Sessa, R. (2015). On the control of riverbed incision induced by run-of-river power plant. *Water Resources Research*, *51*(7), 5023–5040. https://doi.org/10.1002/2014WR016237

Bolognesi, A., Bragalli, C., Lenzi, C., & Artina, S. (2014). Energy Efficiency Optimization in Water Distribution Systems. *Procedia Engineering*, *70*, 181–190. https://doi.org/10.1016/j.proeng.2014.02.021

Boulay, A.-M., Bare, J., Benini, L., Berger, M., Lathuillière, M. J., Manzardo, A., Margni, M., Motoshita, M., Núñez, M., Pastor, A. V., Ridoutt, B., Oki, T., Worbe, S., & Pfister, S. (2018). The WULCA consensus characterization model for water scarcity footprints: Assessing impacts of water consumption based on available water remaining (AWARE). *The International Journal of Life Cycle Assessment*, *23*(2), 368–378. https://doi.org/10.1007/s11367-017-1333-8

Boulay, A.-M., Bulle, C., Deschênes, L., & Margni, M. LCA Characterisation of Freshwater Use on Human Health and Through Compensation, Vol. 15, pp. 193–204. https://doi.org/10.1007/978-94-007-1899-9_19

Brauman, K. A., Daily, G. C., Duarte, T. K.'e., & Mooney, H. A. (2007). The Nature and Value of Ecosystem Services: An Overview Highlighting Hydrologic Services. *Annual Review of Environment and Resources*, *32*(1), 67–98. https://doi.org/10.1146/annurev.energy.32.031306.102758

Bringezu, S., Kaiser, S., Turnau, S., & Mostert, C. (2019). *Bestimmung des Materialfußabdrucks mit ökobilanziellen Methoden und Softwarelösungen: Version 1.1: Generelle Vorgehensweise und beispielhafte Anwendung für Prozesse derCO2-Nutzung.*

Brismar, A. (2002). River systems as providers of goods and services: A basis for comparing desired and undesired effects of large dam projects. *Environmental Management*, *29*(5), 598–609. https://doi.org/10.1007/s00267-001-0058-3

Brown, C. J., Saunders, M. I., Possingham, H. P., & Richardson, A. J. (2013). Managing for interactions between local and global stressors of ecosystems. *PloS One*, *8*(6), e65765. https://doi.org/10.1371/journal.pone.0065765

Burcu, Ç., Güleç, N., & Erler, A. (1997). Geochemical assessment of environmental effects of fly ash from Seyitomer (Kütahya) Power Plant. *GEOENV'97*.

Burkhard, B., Kroll, F., Müller, F., & Windhorst, W. (2009). Landscapes' capacities to provide ecosystem services - A concept for land-cover based assessments. *Landscape Online*, *15*, 1–22. https://doi.org/10.3097/LO.200915

Butturini, A., & Sabater, F. (1998). Ammonium and phosphate retention in a Mediterranean stream: hydrological versus temperature control. *Canadian Journal of Fisheries and Aquatic Sciences*, *55*(8), 1938–1945. https://doi.org/10.1139/cjfas-55-8-1938

Caissie, D. (2006). The thermal regime of rivers: a review. *Freshwater Biology*, *51*(8), 1389–1406. https://doi.org/10.1111/j.1365-2427.2006.01597.x

Campbell, J. A., Laul, J. C., Nielson, K. K., & Smith, R. D. (1978). Separation and chemical characterization of finely-sized fly-ash particles. *Analytical Chemistry*, *50*(8), 1032–1040. https://doi.org/10.1021/ac50030a009

Carolli, M., & Pusch, M. (2018). Assessing linkages between river morphology and ecosystem services provided by alpine rivers: The EU HyMoCARES project. *IS Rivers 2018*.

Carolli, M., Zolezzi, G., Geneletti, D., Siviglia, A., Carolli, F., & Cainelli, O. (2017). Modelling white-water rafting suitability in a hydropower regulated Alpine River. *The Science of the Total Environment*, *579*, 1035–1049. https://doi.org/10.1016/j.scitotenv.2016.11.049

Copp, G. H. (1990). Effect of regulation on 0+ fish recruitment in the great ouse, a lowland river. *Regulated Rivers: Research & Management*, *5*(3), 251–263. https://doi.org/10.1002/rrr.3450050306

Costanza, R., d'Arge, R., Groot, R. de, Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R. V., Paruelo, J., Raskin, R. G., Sutton, P., & van den Belt, M. (1997). The value of the world's ecosystem services and natural capital. *Nature*, *387*(6630), 253–260. https://doi.org/10.1038/387253a0

Costanza, R., Groot, R. de, Sutton, P., van der Ploeg, S., Anderson, S. J., Kubiszewski, I., Farber, S., & Turner, R. K. (2014). Changes in the global value of ecosystem services. *Global Environmental Change*, *26*, 152–158. https://doi.org/10.1016/j.gloenvcha.2014.04.002

Crain, C. M., Kroeker, K., & Halpern, B. S. (2008). Interactive and cumulative effects of multiple human stressors in marine systems. *Ecology Letters*, *11*(12), 1304–1315. https://doi.org/10.1111/j.1461-0248.2008.01253.x

Cronin, J., Anandarajah, G., & Dessens, O. (2018). Climate change impacts on the energy system: A review of trends and gaps. *Climatic Change*, *151*(2), 79–93. https://doi.org/10.1007/s10584-018-2265-4

da Silver, F., de Moraes, J., Vilela, M., Cesar, M., & Mendes, C. (2011). *Diagnóstico hídrico em destilarias de álcool em São Paulo*. https://ainfo.cnptia.embrapa.br/digital/bitstream/item/39538/1/18-46-1-PB.pdf

Dai, A., Qian, T., Trenberth, K. E., & Milliman, J. D. (2009). Changes in Continental Freshwater Discharge from 1948 to 2004. *Journal of Climate*, *22*(10), 2773–2792. https://doi.org/10.1175/2008JCLI2592.1

Daily, G. C. (1997). *Nature's services: Societal dependence on natural ecosystems*. Island Press. http://search.ebscohost.com/login.aspx?direct=true&scope=site&db=nlebk&db=nlabk&AN=117817

Daniell, K. A., & Kay, A. (2017). *Multi-level Governance: Conceptual challenges and case studies from Australia*. ANU Press. http://www.jstor.org/stable/j.ctt1zgwjv0

Datry, T., Pella, H., Leigh, C., Bonada, N., & Hugueny, B. (2016). A landscape approach to advance intermittent river ecology. *Freshwater Biology*, *61*(8), 1200–1213. https://doi.org/10.1111/fwb.12645

Davison, R. L., Natusch, D. F. S., Wallace, J. R., & Evans, C. A. (1974). Trace elements in fly ash. Dependence of concentration on particle size. *Environmental Science & Technology*, *8*(13), 1107–1113. https://doi.org/10.1021/es60098a003

Doyle, M. W., Stanley, E. H., & Harbor, J. M. (2003). Hydrogeomorphic controls on phosphorus retention in streams. *Water Resources Research*, *39*(6), 758. https://doi.org/10.1029/2003WR002038

Dukes, J. S., & Mooney, H. A. (1999). Does global change increase the success of biological invaders? *Trends in Ecology & Evolution*, *14*(4), 135–139. https://doi.org/10.1016/S0169-5347(98)01554-7

Durance, I., & Ormerod, S. J. (2007). Climate change effects on upland stream macroinvertebrates over a 25-year period. *Global Change Biology*, *13*(5), 942–957. https://doi.org/10.1111/j.1365-2486.2007.01340.x

EIA. *Electric Power Annual*.

Elliott, M. A. (Ed.). (1981). *Chemistry of coal utilization. Second supplementary volume*. John Wiley and Sons,New York, NY. https://www.osti.gov/biblio/6001785-chemistry-coal-utilization-second-supplementary-volume

Elosegi, A., Díez, J., & Mutz, M. (2010). Effects of Hydromorphological Integrity on Biodiversity and Functioning of River Ecosystems // Effects of hydromorphological integrity on biodiversity and functioning of river ecosystems. *Hydrobiologia*, *657*(1), 199–215. https://doi.org/10.1007/s10750-009-0083-4

ETC-ICM. (2012). *ETC/ICM Report 1/2012: Ecological and chemical status and pressures in European waters*. https://www.eionet.europa.eu/etcs/etc-icm/products/etc-icm-reports/ecological-and-chemical-status-and-pressures-in-european-waters-etc-icm-technical-report-1-2012

ETC-ICM. (2012). *ETC/ICM Report 2/2012: Hydromorphological alterations and pressures in European rivers, lakes, transitional and coastal waters*. https://www.eionet.europa.eu/etcs/etc-icm/products/etc-icm-reports/hydromorphological-alterations-and-pressures-in-european-rivers-lakes-transitional-and-coastal-waters-etc-icm-technical-report-2-2012

EUREAU. (2009). *statistics overview on water and wastewater in Europe 2008.: Country profiles and European statistics*. Brussels.

Feeley, T. J., Skone, T. J., Stiegel, G. J., McNemar, A., Nemeth, M., Schimmoller, B., Murphy, J. T., & Manfredo, L. (2008). Water: A critical resource in the thermoelectric power industry. *Energy*, *33*(1), 1–11. https://doi.org/10.1016/j.energy.2007.08.007

Field, C. B. (Ed.). (2014). *Climate change 2014: Impacts, adaptation, and vulnerability : Working Group II contribution to the fifth assessment report of the Intergovernmental Panel on Climate Change : Part A: Global and sectoral aspects*. Cambridge University Press. https://doi.org/10.1017/CBO9781107415379

Flörke, M., Schneider, C., & McDonald, R. I. (2018). Water competition between cities and agriculture driven by climate change and urban growth. *Nature Sustainability*, *1*(1), 51–58. https://doi.org/10.1038/s41893-017-0006-8

FNS, & UNICA. (2014). *Gestão dos Recursos Hídricos na Agroindústria Canavieira*. https://unica.com.br/wp-content/uploads/2019/06/Gestao-dos-Recursos-Hidricos.pdf

Foresta, T. S. (2018). *How Does Nevada Use its Scarce Water Resources?* https://guinncenter.org/how-does-nevada-use-its-scarce-water-resources/

Fredén, F. (2011). *Impacts of dams on lowland agriculture in the Mekong. River catchment [*MSc Thesis], Lund, Schweden.

Frid, C., & Raffaelli, D. G. (Eds.). (2010). *Ecological reviews. Ecosystem ecology: A new synthesis*. Cambridge University Press. https://doi.org/10.1017/CBO9780511750458

Fu, B., & Li, N. (2019). Tradeoff between Hydropower and River Visual Landscape Services in Mountainous Areas. *Sustainability*, *11*(19), 5509. https://doi.org/10.3390/su11195509

GADM. (2018). *Country administrative areas: GADM data (version 3.6)*. https://gadm.org/download_country_v3.html

Gehrs, C. W., Shriner, D. S., & Herbes, S. E. (1981). Environmental Health and Safety Implications of Increased Coal Utilization. In M. A. Elliott (Ed.), *Chemistry of coal utilization. Second supplementary volume* (pp. 2194–2219). John Wiley and Sons,New York, NY.

Gelbard, J. L., & Belnap, J. (2003). Roads as Conduits for Exotic Plant Invasions in a Semiarid Landscape. *Conservation Biology*, *17*(2), 420–432. https://doi.org/10.1046/j.1523-1739.2003.01408.x

Giakoumis, T., & Voulvoulis, N. (2018). A participatory ecosystems services approach for pressure prioritisation in support of the Water Framework Directive. *Ecosystem Services*, *34*, 126–135. https://doi.org/10.1016/j.ecoser.2018.10.007

Gjorgiev, B., & Sansavini, G. (2018). Electrical power generation under policy constrained water-energy nexus. *Applied Energy*, *210*, 568–579. https://doi.org/10.1016/j.apenergy.2017.09.011

Graf, W. L. (1999). Dam nation: A geographic census of American dams and their large-scale hydrologic impacts. *Water Resources Research*, *35*(4), 1305–1311. https://doi.org/10.1029/1999WR900016

Grill, G., Lehner, B., Lumsdon, A. E., MacDonald, G. K., Zarfl, C., & Reidy Liermann, C. (2015). An index-based framework for assessing patterns and trends in river fragmentation and flow regulation by global dams at multiple scales. *Environmental Research Letters*, *10*(1), 15001. https://doi.org/10.1088/1748-9326/10/1/015001

Grizzetti, B., Lanzanova, D., Liquete, C., Reynaud, A., & Cardoso, A. C. (2016). Assessing water ecosystem services for water resource management. *Environmental Science & Policy*, *61*, 194–203. https://doi.org/10.1016/j.envsci.2016.04.008

Gulliver, J. S., & Arndt, R. E. A. (Eds.). (1991). *Hydropower engineering handbook*. McGraw-Hill.

Gunkel, G., Lange, U., Walde, D., & Rosa, J. W. C. (2003). The environmental and operational impacts of Curua-Una, a reservoir in the Amazon region of Para, Brazil. *Lakes and Reservoirs: Research and Management*, *8*(3-4), 201–216. https://doi.org/10.1111/j.1440-1770.2003.00227.x

Gupta, H., Kao, S.-J., & Dai, M. (2012). The role of mega dams in reducing sediment fluxes: A case study of large Asian rivers. *Journal of Hydrology*, *464-465*(1–4), 447–458. https://doi.org/10.1016/j.jhydrol.2012.07.038

Haines-Young, R., & Potschin, M. (2010). The links between biodiversity, ecosystem services and human well-being. In C. Frid & D. G. Raffaelli (Eds.), *Ecological reviews. Ecosystem ecology: A new synthesis* (pp. 110–139). Cambridge University Press. https://doi.org/10.1017/CBO9780511750458.007

Halpern, B. S., McLeod, K. L., Rosenberg, A. A., & Crowder, L. B. (2008). Managing for cumulative impacts in ecosystem-based management through ocean zoning. *Ocean & Coastal Management*, *51*(3), 203–211. https://doi.org/10.1016/j.ocecoaman.2007.08.002

Hamiche, A. M., Stambouli, A. B., & Flazi, S. (2016). A review of the water-energy nexus. *Renewable and Sustainable Energy Reviews*, *65*, 319–331. https://doi.org/10.1016/j.rser.2016.07.020

Hansen, L. D., & Fisher, G. L. (1980). Elemental distribution in coal fly ash particles. *Environmental Science & Technology*, *14*(9), 1111–1117. https://doi.org/10.1021/es60169a015

Havel, J. E., Lee, C. E., & Vander Zanden, M. J. (2005). Do Reservoirs Facilitate Invasions into Landscapes? *BioScience*, *55*(6), 518. https://doi.org/10.1641/0006-3568(2005)055[0518:DRFIIL]2.0.CO;2

Havens, K. E., James, R.T., East, T. L., & Smith, V. H. (2003). N:P ratios, light limitation, and cyanobacterial dominance in a subtropical lake impacted by non-point source nutrient pollution. *Environmental Pollution*, *122*(3), 379–390. https://doi.org/10.1016/S0269-7491(02)00304-4

Hecky, R. E., & Kilham, P. (1988). Nutrient limitation of phytoplankton in freshwater and marine environments: A review of recent evidence on the effects of enrichment1. *Limnology and Oceanography*, *33*(4part2), 796–822. https://doi.org/10.4319/lo.1988.33.4part2.0796

Hering, D., Carvalho, L., Argillier, C., Beklioglu, M., Borja, A., Cardoso, A. C., Duel, H., Ferreira, T., Globevnik, L., Hanganu, J., Hellsten, S., Jeppesen, E., Kodeš, V., Solheim, A. L., Nõges, T., Ormerod, S., Panagopoulos, Y., Schmutz, S., Venohr, M., & Birk, S. (2015). Managing aquatic ecosystems and water resources under multiple stress--an introduction to the MARS project. *The Science of the Total Environment*, *503-504*, 10–21. https://doi.org/10.1016/j.scitotenv.2014.06.106

Hertwich, E. G. (2013). Addressing biogenic greenhouse gas emissions from hydropower in LCA. *Environmental Science & Technology*, *47*(17), 9604–9611. https://doi.org/10.1021/es401820p

Hischier, R. (2010). ReCiPe. In R. Hischier & B. Weidema (Eds.), *Implementation of Life Cycle Impact Assessment Methods. ecoinvent report No. 3, Data v2.2* (pp. 143–148).

Hischier, R., & Weidema, B. (Eds.). (2010). *Implementation of Life Cycle Impact Assessment Methods. ecoinvent report No. 3, Data v2.2*. https://www.researchgate.net/publication/263239305_Implementation_of_Life_Cycle_Impact_Assessment_Methods_ecoinvent_report_No_3_v22

Hoekstra, A. Y., Chapagain, A. K., Aldaya, M. M., & Mekonnen, M. M. (2011). *The Water Footprint Assessment Manual: Setting the Global Standard.*

Hoekstra, A. Y., & Hung, P. Q. (2002). Virtual water trade: a quantification of virtual water flows between nations in relation to international crop trade. *Research Report Series*(11), 1–120.

Hoekstra, A. Y. (2017). Water Footprint Assessment: Evolvement of a New Research Field. *Water Resources Management*, *31*(10), 3061–3081. https://doi.org/10.1007/s11269-017-1618-5

Holdren, J. P., & Ehrlich, P. R. (1974). Human population and the global environment. *American Scientist*, *62*(3), 282–292.

Hornung, L. K., Podschun, S. A., & Pusch, M. (2019). Linking ecosystem services and measures in river and floodplain management. *Ecosystems and People*, *15*(1), 214–231. https://doi.org/10.1080/26395916.2019.1656287

Hulett, L. D., WEINBERGER, A. J., NORTHCUTT, K. J., & FERGUSON, M. (1980). Chemical Species in Fly Ash from Coal-Burning Power Plants // Chemical species in fly ash from coal-burning power plants. *Science*, *210*(4476), 1356–1358. https://doi.org/10.1126/science.210.4476.1356

Hulme, P. E. (2009). Trade, transport and trouble: managing invasive species pathways in an era of globalization. *Journal of Applied Ecology*, *46*(1), 10–18. https://doi.org/10.1111/j.1365-2664.2008.01600.x

Hung, N. N. (2011). *Sediment Dynamics in the Floodplain of the Mekong Delta, Vietnam* [Phd.]. University of Stuttgart, Stuttgart.

Hung, N. N., Delgado, J. M., Güntner, A., Merz, B., Bárdossy, A., & Apel, H. (2014). Sedimentation in the floodplains of the Mekong Delta, Vietnam Part II: deposition and erosion. *Hydrological Processes*, *28*(7), 3145–3160. https://doi.org/10.1002/hyp.9855

Hunt, S. D. (2011). Sustainable marketing, equity, and economic growth: a resource-advantage, economic freedom approach. *Journal of the Academy of Marketing Science*, *39*(1), 7–20. https://doi.org/10.1007/s11747-010-0196-3

Hussey, K., & Pittock, J. (2012). The Energy–Water Nexus: Managing the Links between Energy and Water for a Sustainable Future. *Ecology and Society*, *17*(1). https://doi.org/10.5751/ES-04641-170131

Hutcheson, W., Hoagland, P., & Di Jin (2018). Valuing environmental education as a cultural ecosystem service at Hudson River Park. *Ecosystem Services*, *31*, 387–394. https://doi.org/10.1016/j.ecoser.2018.03.005

Ideva, R. J., Machiwa, J., Schiemer, F., & Hein, T. (2008). Effect of an impoundment on nutrient dynamics in the Kihansi River, Tanzania. *African Journal of Aquatic Science*, *33*(2), 181–188. https://doi.org/10.2989/AJAS.2008.33.2.11.508

IEA. (2016). *Water Energy Nexus. In World Energy Outlook 2016*. Paris. International Energy Agency. https://www.iea.org/publications/freepublications/publication/ WorldEnergyOutlook2016ExcerptWaterEnergyNexus.pdf

International Energy Agency. (2019). *Key World Energy Statistics 2019*. OECD. https://doi.org/10.1787/71b3ce84-en

IPCC. (2014). *Climate Change 2014: Synthesis Report*. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

IPCC. (2018). *Global Warming of 1.5°C.An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.*

Izagirre, O., Argerich, A., Martí, E., & Elosegi, A. (2013). Nutrient uptake in a stream affected by hydropower plants: comparison between stream channels and diversion canals. *Hydrobiologia*, *712*(1), 105–116. https://doi.org/10.1007/s10750-012-1354-z

Jans, Y., Berndes, G., Heinke, J., Lucht, W., & Gerten, D. (2018). Biomass production in plantations: Land constraints increase dependency on irrigation water. *GCB Bioenergy*, *10*(9), 628–644. https://doi.org/10.1111/gcbb.12530

Jia, T., Qin, H., Yan, D., Zhang, Z., Liu, B., Li, C., Wang, J., & Zhou, J. (2019). Short-Term Multi-Objective Optimal Operation of Reservoirs to Maximize the Benefits of Hydropower and Navigation. *Water*, *11*(6), 1272. https://doi.org/10.3390/w11061272

Jungbluth, N. (2010). Cumulative energy demand. In R. Hischier & B. Weidema (Eds.), *Implementation of Life Cycle Impact Assessment Methods. ecoinvent report No. 3, Data v2.2* (pp. 33–40).

Jungbluth, N. (2010). IPCC 2001. In R. Hischier & B. Weidema (Eds.), *Implementation of Life Cycle Impact Assessment Methods. ecoinvent report No. 3, Data v2.2* (pp. 126–136).

Jungbluth, N. (2010). IPCC 2007. In R. Hischier & B. Weidema (Eds.), *Implementation of Life Cycle Impact Assessment Methods. ecoinvent report No. 3, Data v2.2* (pp. 136–142).

Karabulut, A., Egoh, B. N., Lanzanova, D., Grizzetti, B., Bidoglio, G., Pagliero, L., Bouraoui, F., Aloe, A., Reynaud, A., Maes, J., Vandecasteele, I., & Mubareka, S. (2016). Mapping water provisioning services to support the ecosystem–water–food–energy nexus in the Danube river basin. *Ecosystem Services*, *17*(1), 278–292. https://doi.org/10.1016/J.ECOSER.2015.08.002

Karageorgis, A. P., Skourtos, M. S., Kapsimalis, V., Kontogianni, A. D., Skoulikidis, N. T., Pagou, K., Nikolaidis, N. P., Drakopoulou, P., Zanou, B., Karamanos, H., Levkov, Z., & Anagnostou, C. (2005). An integrated approach to watershed management within the DPSIR framework: Axios River catchment and Thermaikos Gulf. *Regional Environmental Change*, *5*(2-3), 138–160. https://doi.org/10.1007/s10113-004-0078-7

Kędra, M., & Wiejaczka, Ł. (2018). Climatic and dam-induced impacts on river water temperature: Assessment and management implications. *The Science of the Total Environment*, *626*, 1474–1483. https://doi.org/10.1016/j.scitotenv.2017.10.044

Kelble, C. R., Loomis, D. K., Lovelace, S., Nuttle, W. K., Ortner, P. B., Fletcher, P., Cook, G. S., Lorenz, J. J., & Boyer, J. N. (2013). The EBM-DPSER conceptual model: Integrating ecosystem services into the DPSIR framework. *PloS One*, *8*(8), e70766. https://doi.org/10.1371/journal.pone.0070766

Kemdirim, E. C. (2005). Studies on the hydrochemistry of Kangimi reservoir, Kaduna State, Nigeria. *African Journal of Ecology*, *43*(1), 7–13. https://doi.org/10.1111/j.1365-2028.2005.00427.x

Kenny, J. F., Barber, N. L., Hutson, S. S., Linsey, K. S., Lovelace, J. K., & Maupin, M. A. (2009). *Estimated Use of Water in the United States in 2005: U.S. Geological Survey Circular vol 1344*. Renston, VA. USGS.

Kinoshita, M. Public procurement research: Why the creation of a reasonable competition environment is something the world has not yet see. *Daily Construction Works News Journal*.

Klein, D. H., Andren, A. W., Carter, J. A., Emery, J. F., Feldman, C., Fulkerson, W., Lyon, W. S., Ogle, J. C., & Talmi, Y. (1975). Pathways of thirty-seven trace elements through coal-fired power plant. *Environmental Science & Technology*, *9*(10), 973–979. https://doi.org/10.1021/es60108a007

Koellner, T., & Scholz, R. (2007). Assessment of Land Use Impacts on the Natural Environment. Part 1: An Analytical Framework for Pure Land Occupation and Land Use Change (8 pp). *The International Journal of Life Cycle Assessment*, *12*(1), 16–23. https://doi.org/10.1065/lca2006.12.292.1

Koellner, T., & Scholz, R. W. (2008). Assessment of land use impacts on the natural environment. // Assessment of land use impacts on the natural environment: Part 2: Generic Characterization Factors for Local Species Diversity in Central Europe. *Int J Life Cycle Assessment*, *13*(1), 32–48. https://doi.org/10.1065/lca2006.12.292.2

Kopsick, D. A., & Angino, E. E. (1981). Effect of leachate solutions from fly and bottom ash on groundwater quality. *Journal of Hydrology*, *54*, 341–356.

Kotut, K., Njuguna, S. G., Muthuri, F. M., & Krienitz, L. (1999). The physico-chemical conditions of Turkwel Gorge Reservoir, a new man made lake in Northern Kenya. *Limnologica*, *29*(4), 377–392. https://doi.org/10.1016/S0075-9511(99)80046-2

Kristensen, P. (2004). *The DPSIR framework. National Environment Research Institute*. https://scholar.google.com/citations?user=rbi5bfaaaaaj&hl=de&oi=sra

Kuenzer, C., Campbell, I., Roch, M., Leinenkugel, P., Tuan, V. Q., & Dech, S. (2013). Understanding the impact of hydropower developments in the context of upstream–downstream relations in the Mekong river basin. *Sustainability Science*, *8*(4), 565–584. https://doi.org/10.1007/s11625-012-0195-z

Landwehr, T., Schomber, A., & Pahl-Wostl, C. A holistic and globally applicable indication system for regional electric-energy-water security. *Ecosystem Health and Sustainability*.

Lange, K., Meier, P., Trautwein, C., Schmid, M., Robinson, C. T., Weber, C., & Brodersen, J. (2018). Basin-scale effects of small hydropower on biodiversity dynamics. *Frontiers in Ecology and the Environment*, *16*(7), 397–404. https://doi.org/10.1002/fee.1823

Lemoine, Y., & Bellet, L. (2015). Water for energy framework - evaluation of the local interactions between energy sites and water - general report. *World Water Council*. https://www.worldwater-council.org/en/7th-world-water-forum-daegu-gyeongbuk-2015

Li, J., Dong, S., Yang, Z., Peng, M., Liu, S., & Li, X. (2012). Effects of cascade hydropower dams on the structure and distribution of riparian and upland vegetation along the middle-lower Lancang-Mekong River. *Forest Ecology and Management*, *284*, 251–259. https://doi.org/10.1016/j.foreco.2012.07.050

Liang, C., Xin, S., Dongsheng, W., Xiuying, Y., & Guodong, J. (2016). The ecological benefit–loss evaluation in a riverine wetland for hydropower projects – A case study of Xiaolangdi reservoir in the Yellow River, China. *Ecological Engineering*, *96*(1), 34–44. https://doi.org/10.1016/j.ecoleng.2015.12.037

Liew, J. H., Tan, H. H., & Yeo, D. C. J. (2016). Dammed rivers: impoundments facilitate fish invasions. *Freshwater Biology*, *61*(9), 1421–1429. https://doi.org/10.1111/fwb.12781

Logan, L. H., & Stillwell, A. S. (2018). Probabilistic assessment of aquatic species risk from thermoelectric power plant effluent: Incorporating biology into the energy-water nexus. *Applied Energy*, *210*, 434–450. https://doi.org/10.1016/j.apenergy.2017.09.027

Logan, L. H., & Stillwell, A. S. (2018). Water Temperature Duration Curves for Thermoelectric Power Plant Mixing Zone Analysis. *Journal of Water Resources Planning and Management*, *144*(9), 4018058. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000980

Lohrmann, A., Farfan, J., Caldera, U., Lohrmann, C., & Breyer, C. (2019). Global scenarios for significant water use reduction in thermal power plants based on cooling water demand estimation using satellite imagery. *Nature Energy*, *4*(12), 1040–1048. https://doi.org/10.1038/s41560-019-0501-4

Lu, C. X., Xie, G. D., & Cheng, S. K. (2001). Economic Evaluation of River Ecosystem Service in Recreation. *Resour. Sci.*, *23*, 77–81.

Lubega, W. N., & Farid, A. M. (2016). A Reference System Architecture for the Energy–Water Nexus. *IEEE Systems Journal*, *10*(1), 106–116. https://doi.org/10.1109/JSYST.2014.2302031

MacIsaac, H. J., Borbely, J. V. M., Muirhead, J. R., & Graniero, P. A. (2004). BACKCASTING AND FORECASTING BIOLOGICAL INVASIONS OF INLAND LAKES. *Ecological Applications*, *14*(3), 773–783. https://doi.org/10.1890/02-5377

Maes, J., Teller, A., Erhard, M., Liquete, C., Braat, L., Berry, P., Egoh, B., Puydarrieux, P., Fiorina, S. F., Paracchini, M. L., Keune, H., Wittmer, H., Hauck, J., Fiala, I., Verburg, P. H., Condé, S., Schägner, J. P., San Miguel, J., Estreguil, C., . . . Connor, D. Bidoglio, G. (2013). *An analytical framework for ecosystem assessments under action 5 of the EU Biodiversity Strategy to 2020: Discussion paper, final, April 2013. Technical report: 2013-067*. European Commission Environment. http://ec.europa.eu/environment/nature/knowledge/ecosystem_assessment/pdf/MAESWorkingPaper2013.pdf

Maes, J., Teller, A., Erhard, M., Murphy, P., Paracchini, M. L., Barredo, J. I., Grizzetti, B., Cardoso, A. C., Somma, F., & Petersen, J.E, et. al. (2012). *European waters: Assessment of status and pressures*. *EEA report: Vol. 2012,8*. European Environment Agency. http://publications.europa.eu/en/publication-detail/-/publication/9ac92adc-2a06-4bdb-8eac-fdc95e6e68cb

Manh, N. V., Dung, N. V., Hung, N. N., Merz, B., & Apel, H. (2014). Large-scale suspended sediment transport and sediment deposition in the Mekong Delta. *Hydrology and Earth System Sciences*, *18*(8), 3033–3053. https://doi.org/10.5194/hess-18-3033-2014

Marti, E., Aumatell, J., Godé, L., Poch, M., & Sabater, F. (2004). Nutrient retention efficiency in streams receiving inputs from wastewater treatment plants. *Journal of Environmental Quality*, *33*(1), 285–293. https://doi.org/10.2134/jeq2004.2850

Maulbetsch, J., & Stallings, J. (2012, November 1). Evaluating the Economics of Alternative Cooling Technologies. *Power Engineering,* 2012. https://www.power-eng.com/coal/evaluat-economics-alternative-cool-technologies/

Mekonnen, M. M., Gerbens-Leenes, P. W., & Hoekstra, A. Y. (2015). The consumptive water footprint of electricity and heat: a global assessment. *Environmental Science: Water Research & Technology*, *1*(3), 285–297. https://doi.org/10.1039/C5EW00026B

Miara, A., Vörösmarty, C. J., Stewart, R. J., Wollheim, W. M., & Rosenzweig, B. (2013). Riverine ecosystem services and the thermoelectric sector: Strategic issues facing the Northeastern United States. *Environmental Research Letters*, *8*(2), 25017. https://doi.org/10.1088/1748-9326/8/2/025017

Miglietta, P., Morrone, D., & Leo, F. de (2018). The Water Footprint Assessment of Electricity Production: An Overview of the Economic-Water-Energy Nexus in Italy. *Sustainability*, *10*(1), 228. https://doi.org/10.3390/su10010228

Monfreda, C., Ramankutty, N., & Foley, J. A. (2008). Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. *Global Biogeochemical Cycles*, *22*(1), n/a-n/a. https://doi.org/10.1029/2007GB002947

Morgan, D. E., Keser, M., Swenarton, J. T., & Foertch, J. F. (2003). Population dynamics of the Asiatic clam, Corbicula fluminea (Müller) in the Lower Connecticut River: Establishing a foothold in New England. *Journal of Shellfish Research*, *22*(1), 193–203. https://www.researchgate.net/publication/285760144_Population_dynamics_of_the_Asiatic_clam_Corbicula_fluminea_Muller_in_the_Lower_Connecticut_River_Establishing_a_foothold_in_New_England

Mostert, & Bringezu (2019). Measuring Product Material Footprint as New Life Cycle Impact Assessment Method: Indicators and Abiotic Characterization Factors. *Resources*, *8*(2), 61. https://doi.org/10.3390/resources8020061

Mundialis. (2020). *Current and future potential sugarcane expanssion* [shapefile].

Muralikrishna, I. V., & Manickam, V. (2017). Life Cycle Assessment. *Science and Engineering for Industry*, 57–75. https://doi.org/10.1016/B978-0-12-811989-1.00005-1

Mwaura, F. (2010). Some aspects of water quality characteristics in small shallow tropical man-made reservoirs in Kenya. *African Journal of Science and Technology*, *7*(1), 82–96. https://doi.org/10.4314/ajst.v7i1.55203

Mwaura, F., Mavuti, K. M., & Wamicha, W. N. (2002). Biodiversity characteristics of small high-altitude tropical man-made reservoirs in the Eastern Rift Valley, Kenya. *Lakes and Reservoirs: Research and Management*, *7*(1), 1–12. https://doi.org/10.1046/j.1440-1770.2002.00162.x

Narvaez Marulanda et al. (2021) [Manuscript in preparation]

Neteler, M., Bowman, M.H., Landa, M. and Metz, M. (2012). GRASS GIS: a multi-purpose Open Source GIS. Environmental Modelling & Software, 31: 124-130. https://dx.doi.org/10.1016/j.envsoft.2011.11.014

Neteler, M., Gebbert, S., Tawalika, C., Bettge, A., Benelcadi, H., Löw, F., Adams, T., Paulsen, H. (2019). Actinia: cloud based geoprocessing. In: Proc. of the 2019 conference on Big Data from Space (BiDS’2019) (pp. 41–44). EUR 29660 EN, Publications Office of the European Union 5, Luxembourg: P. Soille, S. Loekken, and S. Albani (Eds.). http://doi.org/10.5281/zenodo.2631917

Neto, A. E. (2015). *Management of Water Resources in the Sugarcane Agro-Industry in Brazil: Workshop on “Examples of Positive Bioenergy and Water Relationships”*. Royal Swedish Academy of Agriculture and Science (KSLA). http://www.globalbioenergy.org/fileadmin/user_upload/gbep/docs/2015_events/AG6_workshop_25-26_August_2015/25_Aug_7_Elia.pdf

Nõges, P., Argillier, C., Borja, Á., Garmendia, J. M., Hanganu, J., Kodeš, V., Pletterbauer, F., Sagouis, A., & Birk, S. (2016). Quantified biotic and abiotic responses to multiple stress in freshwater, marine and ground waters. *The Science of the Total Environment*, *540*, 43–52. https://doi.org/10.1016/j.scitotenv.2015.06.045

Novacanca. *Usinas de açúcar e álcool no estado: Goiás: lista das unidades em operação.* https://www.novacana.com/usinas_brasil/estados/goias

Novak, P. (1997). *Hydraulic structures* (2. ed., reprint). Spon.

O. O., D., Ozgenc, I., & Sozbilir H. (Eds.). *International Earth Sciences Colloquium on the Aegean Region IESCA – 2000.*

Ocko, I. B., & Hamburg, S. P. (2019). Climate Impacts of Hydropower: Enormous Differences among Facilities and over Time. *Environmental Science & Technology*, *53*(23), 14070–14082. https://doi.org/10.1021/acs.est.9b05083

O'Hanley, J. R., Pompeu, P. S., Louzada, M., Zambaldi, L. P., & Kemp, P. S. (2020). Optimizing hydropower dam location and removal in the São Francisco river basin, Brazil to balance hydropower and river biodiversity tradeoffs. *Landscape and Urban Planning*, *195*(4), 103725. https://doi.org/10.1016/j.landurbplan.2019.103725

Ozkahraman, C. (2017). Water power: the domestic and geostrategic dimensions of Turkey's GAP Project. *Conflict, Security & Development*, *17*(5), 411–428. https://doi.org/10.1080/14678802.2017.1371988

Pahl-Wostl, C. (2015). *Water Governance in the Face of Global Change*. Springer International Publishing. https://doi.org/10.1007/978-3-319-21855-7

Pan, S.-Y., Snyder, S. W., Packman, A. I., Lin, Y. J., & Chiang, P.-C. (2018). Cooling water use in thermoelectric power generation and its associated challenges for addressing water-energy nexus. *Water-Energy Nexus*, *1*(1), 26–41. https://doi.org/10.1016/j.wen.2018.04.002

Pandolfo, T. J., Cope, W. G., & Arellano, C. (2010). Thermal tolerance of juvenile freshwater mussels (Unionidae) under the added stress of copper. *Environmental Toxicology and Chemistry*, *29*(3), 691–699. https://doi.org/10.1002/etc.92

Pearse-Smith, S. W. D. (2012). The Impact of Continued Mekong Basin Hydropower Development on Local Livelihoods. Advance online publication. https://doi.org/10.7916/D85X28NG

Peterson, B. J., Wollheim, W. M., Mulholland, P. J., Webster, J. R., Meyer, J. L., Tank, J. L., Marti, E., Bowden, W. B., Valett, H. M., Hershey, A. E., McDowell, W. H., Dodds, W. K., Hamilton, S. K., Gregory, S., & Morrall, D. D. (2001). Control of nitrogen export from watersheds by headwater streams. *Science (New York, N.Y.)*, *292*(5514), 86–90. https://doi.org/10.1126/science.1056874

Petr, T. (1978). Tropical man-made lakes — their ecological impact. *Archives Hydrobiologia*, *81*, 368–385.

Petts, G. E. (1984). *Impounded Rivers—Perspectives for Ecological Management*. John Wiley.

Petts, G. E., & Gurnell, A. M. (2005). Dams and geomorphology: Research progress and future directions. *Geomorphology*, *71*(1-2), 27–47. https://doi.org/10.1016/j.geomorph.2004.02.015

Pfister, S., Koehler, A., & Hellweg, S. (2009). Assessing the Environmental Impacts of Freshwater Consumption in LCA // Assessing the environmental impacts of freshwater consumption in LCA. *Environmental Science & Technology*, *43*(11), 4098–4104. https://doi.org/10.1021/es802423e

Pflüger, Y., Rackham, A., & Larned, S. (2010). The aesthetic value of river flows: An assessment of flow preferences for large and small rivers. *Landscape and Urban Planning*, *95*(1-2), 68–78. https://doi.org/10.1016/j.landurbplan.2009.12.004

Piggott, J. J., Townsend, C. R., & Matthaei, C. D. (2015). Reconceptualizing synergism and antagonism among multiple stressors. *Ecology and Evolution*, *5*(7), 1538–1547. https://doi.org/10.1002/ece3.1465

Poff, N. L., Allan, J. D., Bain, M. B., Karr, J. R., Prestegaard, K. L., Richter, B. D., Sparks, R. E., & Stromberg, J. C. (1997). The Natural Flow Regime. *BioScience*, *47*(11), 769–784. https://doi.org/10.2307/1313099

Poff, N. L., & Hart, D. D. (2002). How Dams Vary and Why It Matters for the Emerging Science of Dam Removal. *BioScience*, *52*(8), 659. https://doi.org/10.1641/0006-3568(2002)052[0659:HDVAWI]2.0.CO;2

Poff, N. L., Olden, J. D., Merritt, D. M., & Pepin, D. M. (2007). Homogenization of regional river dynamics by dams and global biodiversity implications. *Proceedings of the National Academy of Sciences of the United States of America*, *104*(14), 5732–5737. https://doi.org/10.1073/pnas.0609812104

Potschin, M., & Haines-Young, R. (2013). Landscapes, sustainability and the place-based analysis of ecosystem services. *Landscape Ecology*, *28*(6), 1053–1065. https://doi.org/10.1007/s10980-012-9756-x

Raptis, C. E., van Vliet, M. T. H., & Pfister, S. (2016). Global thermal pollution of rivers from thermoelectric power plants. *Environmental Research Letters*, *11*(10), 104011. https://doi.org/10.1088/1748-9326/11/10/104011

Räsänen, T. A., Someth, P., Lauri, H., Koponen, J., Sarkkula, J., & Kummu, M. (2017). Observed river discharge changes due to hydropower operations in the Upper Mekong Basin. *Journal of Hydrology*, *545*(7), 28–41. https://doi.org/10.1016/j.jhydrol.2016.12.023

Reid, W. V. (2005). *Ecosystems and human well-being: Synthesis ; a report of the Millennium Ecosystem Assessment*. Island Press. http://www.loc.gov/catdir/enhancements/fy0666/2005010265-d.html

Rhoades, S. A. (1995). Market share inequality, the HHI, and other measures of the firm-composition of a market. *Review of Industrial Organization*, *10*(6), 657–674. https://doi.org/10.1007/BF01024300

Rodriguez, D. J., Delgado, A., DeLaquil, P., & Sohns, A. (2013). *Thirsty Energy*. World Bank, Washington, DC. https://openknowledge.worldbank.org/handle/10986/16536

Rogers, P. (2002). Water is an economic good: How to use prices to promote equity, efficiency, and sustainability. *Water Policy*, *4*(1), 1–17. https://doi.org/10.1016/S1366-7017(02)00004-1

Rosa, I. C., Pereira, J. L., Costa, R., Gonçalves, F., & Prezant, R. (2012). Effects of upper-limit water temperatures on the dispersal of the Asian clam Corbicula fluminea. *PloS One*, *7*(10), e46635. https://doi.org/10.1371/journal.pone.0046635

Rosenberg, D. M., Mccully, P., & Pringle, C. M. (2000). Global-Scale Environmental Effects of Hydrological Alterations: Introduction. *BioScience*, *50*(9), 746–751. https://doi.org/10.1641/0006-3568(2000)050[0746:GSEEOH]2.0.CO;2

Rubin, E. S. (1999). Toxic Releases from Power Plants. *Environmental Science & Technology*, *33*(18), 3062–3067. https://doi.org/10.1021/es990018d

Rudorff, B. F. T., Aguiar, D. A., Silva, W. F., Sugawara, L. M., Adami, M., & Moreira, M. A. (2010). Studies on the Rapid Expansion of Sugarcane for Ethanol Production in São Paulo State (Brazil) Using Landsat Data. *Remote Sensing*, *2*(4), 1057–1076. https://doi.org/10.3390/rs2041057

Sahin, O., Stewart, R. A., Giurco, D., & Porter, M. G. (2017). Renewable hydropower generation as a co-benefit of balanced urban water portfolio management and flood risk mitigation. *Renewable and Sustainable Energy Reviews*, *68*(1), 1076–1087. https://doi.org/10.1016/j.rser.2016.01.126

Schär, C., Vidale, P. L., Lüthi, D., Frei, C., Häberli, C., Liniger, M. A., & Appenzeller, C. (2004). The role of increasing temperature variability in European summer heatwaves. *Nature*, *427*(6972), 332–336. https://doi.org/10.1038/nature02300

Scherer, L., & Pfister, S. (2016). Global water footprint assessment of hydropower. *Renewable Energy*, *99*, 711–720. https://doi.org/10.1016/j.renene.2016.07.021

Scherer, L., & Pfister, S. (2016). Hydropower's Biogenic Carbon Footprint. *PloS One*, *11*(9), e0161947. https://doi.org/10.1371/journal.pone.0161947

Schindler, D. W. (2001). The cumulative effects of climate warming and other human stresses on Canadian freshwaters in the new millennium. *Canadian Journal of Fisheries and Aquatic Sciences*, *58*(1), 18–29. https://doi.org/10.1139/f00-179

Schindler, D. E., Rogers, D. E., Scheuerell, M. D., & Abrey, C. A. (2005). Effects of changing climate on zooplankton and juvenile sockeye salmon growth in southwestern Alaska. *Ecology*, *86*(1), 198–209. https://doi.org/10.1890/03-0408

Schinegger, R., Trautwein, C., Melcher, A., & Schmutz, S. (2012). Multiple human pressures and their spatial patterns in European running waters. *Water and Environment Journal : The Journal*, *26*(2), 261–273. https://doi.org/10.1111/j.1747-6593.2011.00285.x

Schomberg, A. C., Bringezu, S., & Flörke, M. (2021). Extended life cycle assessment reveals the spatially-explicit water scarcity footprint of a lithium-ion battery storage. *Communications Earth & Environment*, *2*(1), 1. https://doi.org/10.1038/s43247-020-00080-9

Scott, C. A., Pierce, S. A., Pasqualetti, M. J., Jones, A. L., Montz, B. E., & Hoover, J. H. (2011). Policy and institutional dimensions of the water–energy nexus. *Energy Policy*, *39*(10), 6622–6630. https://doi.org/10.1016/j.enpol.2011.08.013

Sesma-Martín, D. (2019). The River's Light: Water Needs for Thermoelectric Power Generation in the Ebro River Basin, 1969–2015. *Water*, *11*(3), 441. https://doi.org/10.3390/w11030441

Sharvini, S. R., Noor, Z. Z., Chong, C. S., Stringer, L. C., & Yusuf, R. O. (2018). Energy consumption trends and their linkages with renewable energy policies in East and Southeast Asian countries: Challenges and opportunities. *Sustainable Environment Research*, *28*(6), 257–266. https://doi.org/10.1016/j.serj.2018.08.006

Shi, W., Chen, Y., Chen, Q., & Liu, D. (2020). Dynamics of heat transport across sediment deposited hyporheic zone inside reservoirs following hydropower production. *The Science of the Total Environment*, *707*, 135611. https://doi.org/10.1016/j.scitotenv.2019.135611

SIEG. (2004). *Sistema Estadual de Geoinformação: Recursos Hídricos - Bacias Hidrográficas: Goiás State*. http://www.sieg.go.gov.br/siegdownloads/

Silici, S., Uluozlu, O. D., Tuzen, M., & Soylak, M. (2016). Honeybees and honey as monitors for heavy metal contamination near thermal power plants in Mugla, Turkey. *Toxicology and Industrial Health*, *32*(3), 507–516. https://doi.org/10.1177/0748233713503393

Skoulikidis, N. T. (2009). The environmental state of rivers in the Balkans--a review within the DPSIR framework. *The Science of the Total Environment*, *407*(8), 2501–2516. https://doi.org/10.1016/j.scitotenv.2009.01.026

Slorach, P. C., Jeswani, H. K., Cuéllar-Franca, R., & Azapagic, A. (2020). Environmental sustainability in the food-energy-water-health nexus: A new methodology and an application to food waste in a circular economy. *Waste Management (New York, N.Y.)*, *113*, 359–368. https://doi.org/10.1016/j.wasman.2020.06.012

Smeets, E., & Weterings, R. (1999). *Environmental indicators: Typology and overview*.

Smith, V. H., Tilman, G. D., & Nekola, J. C. (1999). Eutrophication: impacts of excess nutrient inputs on freshwater, marine, and terrestrial ecosystems. *Environmental Pollution*, *100*(1-3), 179–196. https://doi.org/10.1016/S0269-7491(99)00091-3

Solow, R. M. (2008). The Economics of Resources or the Resources of Economics. *Journal of Natural Resources Policy Research*, *1*(1), 69–82. https://doi.org/10.1080/19390450802504048

Sovacool, B. K., & Gilbert, A. (2014). *Developing Adaptive and Integrated Strategies for Managing the Electricity-Water Nexus.* Univ. Richmond Law Rev. https://scholarship.richmond.edu/lawreview/vol48/iss3/6

Steinhurst W., Knight P., & Schultz M. (2012). *Hydropower Greenhouse Gas Emissions: State of the Research*. https://www.nrc.gov/docs/ML1209/ML12090A850.pdf

Steinmann, Z. J. N., Schipper, A. M., Hauck, M., & Huijbregts, M. A. J. (2016). How Many Environmental Impact Indicators Are Needed in the Evaluation of Product Life Cycles? *Environmental Science & Technology*, *50*(7), 3913–3919. https://doi.org/10.1021/acs.est.5b05179

Stewart, R. J., Wollheim, W. M., Miara, A., Vörösmarty, C. J., Fekete, B., Lammers, R. B., & Rosenzweig, B. (2013). Horizontal cooling towers: riverine ecosystem services and the fate of thermoelectric heat in the contemporary Northeast US. *Journal of Shellfish Research*, *8*(2), 25010. https://doi.org/10.1088/1748-9326/8/2/025010

Sun, H., Sui, X., He, D., Li, X., & Chen, Y. (2019). Fish systematic conservation planning in the Jinsha River Basin. *Acta Hydrobiologica Sinica*.

Swyngedouw, E., & McNeill, J. (2017). Liquid Power: Contested Hydro-Modernities in Twentieth-Century Spain. By Erik Swyngedouw. *Environmental History*, *22*(1), 160–161. https://doi.org/10.1093/envhis/emw094

TEEB. (2010). *Mainstreaming the economics of nature: A synthesis of the approach, conclusions and recommendations of teeb. The economics of ecosystems & biodiversity*. TEEB.

Teichert, N., Borja, A., Chust, G., Uriarte, A., & Lepage, M. (2016). Restoring fish ecological quality in estuaries: Implication of interactive and cumulative effects among anthropogenic stressors. *The Science of the Total Environment*, *542*(Pt A), 383–393. https://doi.org/10.1016/j.scitotenv.2015.10.068

Thomas, S. A., Valett, H. M., Mulholland, P. J., Fellows, C. S., Webster, J. R., Dahm, C. N., & Peterson, C. G. (2001). Nitrogen retention in headwater streams: The influence of groundwater-surface water exchange. *TheScientificWorldJournal*, *1 Suppl 2*, 623–631. https://doi.org/10.1100/tsw.2001.272

Tran, D. D., & Weger, J. (2018). Barriers to Implementing Irrigation and Drainage Policies in An Giang Province, Mekong Delta, Vietnam. *Irrigation and Drainage*, *67*, 81–95. https://doi.org/10.1002/ird.2172

UNCCD. *United Nations Convention to Combat Desertification : Land and Drought*. https://www.unccd.int/issues/land-and-drought

van de Graaf, T., & Colgan, J. (2016). Global energy governance: a review and research agenda. *Palgrave Communications*, *2*(1), 92. https://doi.org/10.1057/palcomms.2015.47

van Vliet, M. T.H., Franssen, W. H.P., Yearsley, J. R., Ludwig, F., Haddeland, I., Lettenmaier, D. P., & Kabat, P. (2013). Global river discharge and water temperature under climate change. *Global Environmental Change*, *23*(2), 450–464. https://doi.org/10.1016/j.gloenvcha.2012.11.002

Vassolo, S., & Döll, P. (2005). Global-scale gridded estimates of thermoelectric power and manufacturing water use. *Water Resources Research*, *41*(4). https://doi.org/10.1029/2004WR003360

Vermaat, J. E., Wagtendonk, A. J., Brouwer, R., Sheremet, O., Ansink, E., Brockhoff, T., Plug, M., Hellsten, S., Aroviita, J., Tylec, L., Giełczewski, M., Kohut, L., Brabec, K., Haverkamp, J., Poppe, M., Böck, K., Coerssen, M., Segersten, J., & Hering, D. (2016). Assessing the societal benefits of river restoration using the ecosystem services approach. *Hydrobiologia*, *769*(1), 121–135. https://doi.org/10.1007/s10750-015-2482-z

Verones, F., Hanafiah, M. M., Pfister, S., Huijbregts, M. A. J., Pelletier, G. J., & Koehler, A. (2010). Characterization factors for thermal pollution in freshwater aquatic environments. *Environmental Science & Technology*, *44*(24), 9364–9369. https://doi.org/10.1021/es102260c

Vitule, J. R. S., Skóra, F., & Abilhoa, V. (2012). Homogenization of freshwater fish faunas after the elimination of a natural barrier by a dam in Neotropics. *Diversity and Distributions*, *18*(2), 111–120. https://doi.org/10.1111/j.1472-4642.2011.00821.x

Vörösmarty, C. J., McIntyre, P. B., Gessner, M. O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S. E., Sullivan, C. A., Liermann, C. R., & Davies, P. M. (2010). Global threats to human water security and river biodiversity. *Nature*, *467*(7315), 555–561. https://doi.org/10.1038/nature09440

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

Ward, J. V., Malard, F., & Tockner, K. (2002). Landscape ecology: A framework for integrating pattern and process in river corridors. *Landscape Ecology*, *17*(1suppl), 35–45. https://doi.org/10.1023/A:1015277626224

Ward, J. V., & Stanford, J. A. (1979). *The Ecology of Regulated Streams*. Plenum Press.

Ward, J. V., Tockner, K., & Schiemer, F. (1999). Biodiversity of floodplain river ecosystems: ecotones and connectivity1. *Regulated Rivers: Research & Management*, *15*(1-3), 125–139. https://doi.org/10.1002/(SICI)1099-1646(199901/06)15:1/3<125::AID-RRR523>3.0.CO;2-E

Welcomme, R. L. (1985). *River fisheries*. *FAO fisheries technical paper: Vol. 262.*

Werner Platzer, Inga Boie, Mario Ragwitz, Christoph Kost, & Thomas Schlegl. (2016). *Supergrid – Approach for the integration of renewable energy in Europe and North Africa*. https://www.researchgate.net/publication/304526594_Supergrid_-_Approach_for_the_integration_of_renewable_energy_in_Europe_and_North_Africa

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): Overview and methodology. *Int J Life Cycle Assess*, *21*(9), 1218–1230. https://doi.org/10.1007/s11367-016-1087-8

WHO. (2018). *A global overview of national regulations and standards for drinkingwater quality*. Geneva.

Wilson, W., Leipzig, T., & Griffiths-Sattenspiel, B. (2012). Burning Our Rivers: The Water Footprint of Electricity. *River Network.*

Winterbone, D., & Turan, A. (2015). *Advanced Thermodynamics for Engineers*. Elsevier. https://doi.org/10.1016/C2013-0-13437-X

World Bank. (2018). *Thirsty energy - summary of the initiative*. https://www.worldbank.org/en/topic/water/brief/water-energy-nexus

Xiong, W., Wang, H., Wang, Q., Tang, J., Bowler, P., Xie, D., Pan, L., & Wang, Z. (2018). Non-native species in the Three Gorges Dam Reservoir: status and risks. *BioInvasions Records*, *7*(2), 153–158. https://doi.org/10.3391/bir.2018.7.2.06

Yanmaz, A. M., & Gunindi, M.E. Capacity benefit–cost relation for concrete gravity RCC Dams. *World Water Environmental Resources Congress*, 88–96.

Zarfl, C., Lumsdon, A. E., Berlekamp, J., Tydecks, L., & Tockner, K. (2015). A global boom in hydropower dam construction. *Aquatic Sciences*, *77*(1), 161–170. https://doi.org/10.1007/s00027-014-0377-0

Zhang, P., Cai, Y., Yang, W., Yi, Y., Yang, Z., & Fu, Q. (2019). Multiple spatio-temporal patterns of vegetation coverage and its relationship with climatic factors in a large dam-reservoir-river system. *Ecological Engineering*, *138*, 188–199. https://doi.org/10.1016/j.ecoleng.2019.07.016

Zhang, P., Cai, Y., Yang, W., Yi, Y., Yang, Z., & Fu, Q. (2020). Contributions of climatic and anthropogenic drivers to vegetation dynamics indicated by NDVI in a large dam-reservoir-river system. *Journal of Cleaner Production*, *256*(4), 120477. https://doi.org/10.1016/j.jclepro.2020.120477

Ziolkowska, J. R., & Peterson, J. M. (Eds.). (2017). *Competition for water resources: Experiences and management approaches in the US and Europe*. Elsevier. http://www.sciencedirect.com/science/book/9780128032374

3 Case Studies

3.1 Coal Power Plant – Heyden, River Weser, Germany

Authors: Swantje Dettmann, Sarah Dickel, Tobias Vogtmann, Stephan Theobald, Anna Schomberg

3.1.1 General overview of the case study

Case study 1 – Weser Drainage Basin

As part of case study 1, recent technical options are being developed for the efficient management of the available water resources and a reduction in the negative impacts of selected energy systems on water as a resource. These are being implemented on a regional basis for River Weser. For this purpose, control strategies, as well as a simulation tool for operational and supra-regional management of hydraulic infrastructure, are being further developed.

To model the water availability on Weser river, a simulation-based predictive optimisation tool for the Eder dam was developed and the watercourse system up to the Hann. Münden gauge expanded till River Diemel, including the Diemel dam and River Weser up to Petershagen gauge. Figure 3-1 illustrates the catchment area of river Weser. The modelled river system is approx. 405 km long and is marked by a red circle. The two dams, Eder dam and Diemel dam, are indicated by arrows with question marks, as their output is considered in the optimisation and their influence on the connected flow system is being analysed.

In the project area, several locally and supraregionally acting water infrastructures are present. Supraregional infrastructures, such as dams, can be used to meet management targets far downstream. Thus, the model can be utilised to make River Weser navigable or to maintain certain minimum water levels or drains at the Weser gauges. In addition to a temporal redistribution of the water, it is used for energy generation by hydropower plants or by drawing off water for cooling purposes at the Heyden coal-fired power station. However, the dams have multiple usage aspects: the Eder dam with a storage space of 200 million m^3 is used to compensate for low seasonal water levels, improve the shipping conditions from Hann. Münden, prevent floods and generate power. The Diemel dam has a storage volume of approx. 20 million m^3; it facilitates water level regulation on River Weser and the Mittelland Canal, flood protection and electricity generation.

Figure 3-1: Graphical overview of Weser catchment with the modelled area (red circle); Eder dam (ETS) and Diemel dam (DTS) are represented as arrows

As part of the project, the Department of Hydraulic Engineering and Water Management at the University of Kassel conducted a large-scale modelling of water availability on the Upper Weser. Thus, the supraregional effect of the management was examined too, possible changes in the supply (climate change) were considered. For these studies, an existing simulation-based predictive optimisation model of the Eder dam with a flowing water system was expanded. The upstream river section, up to the Petershagen gauge, the tributary Diemel and the Diemel dam have been added to the model. This enables an analysis of water use and distribution along the Weser, taking into account competing users (shipping, water abstraction, etc.). The key parameter here is the temporal flow behaviour at selected stations. By simulating different scenarios, discharge strategies for an adapted management strategy can be investigated. These scenarios include supporting discharges for shipping or in the event of low water conditions and flood situations. This enables the evaluation of control concepts and the identification of the potential for improvement against the background of efficient management of the existing water resources. In case forecast data are submitted, the model can be used in practice as a decision support system for the determination of the optimal control strategy for the supraregional management of hydraulic engineering infrastructures.

3.1.2 Direct impacts of the energy system on water resources

The total quantitative water scarcity footprint (WSF_{quan}) of the coal-fired power plant Heyden is 0.009 m^3 kWh^{-1} with most of it associated with the operation phase (Table 3-1). The total qualitative water scarcity footprint (WSF_{qual}) is approximately 2 m^3 kWh^{-1} significantly higher; again, most of it can be attributed to the operation phase (Table 3-1). However, direct contributions only come from quantitative water use during the operation phase. They account for 23% of the total WSF_{quan} of the operation phase and represent evaporation losses from the cooling tower. Fittingly, the hotspot analysis of the indicators WSF_{quan} and WSF_{qual} has not revealed on-site hotspots of water use of the coal power plant according to the used methodology (described in Section 2.1, see also Figure 2-4).

3.1.3 Indirect impacts of the energy system on water resources

Apart from direct contribution from the operation phase, all other contributions to the water scarcity footprint (WSF) come from the upstream supply chain (Table 3-1) and are therefore associated with indirect impacts. The WSF_{quan} of the construction phase is related to upstream processes that provide hard coal, steel, iron or copper, and electricity for the upstream supply chain. The WSF_{quan} of the operation phase is slightly higher and associated with 77% remote contributions, which come predominately from hard coal mining in Russian mines (for details of the life cycle assessment [LCA] model, see Appendix A). The WSF_{qual} is significantly higher, especially for the operation phase. As only direct emissions of aluminium to water bodies are considered for the calculation of WSF_{qual} (for a detailed explanation of the indicator see Section 2.1), such processes with high aluminium emissions are particularly prominent here and in the other case studies. In this case, we are talking about processes for treating waste from coal combustion in Switzerland, Greece and at unspecified locations. This is the first indication in this study of multiple environmental harms associated with coal-fired electricity.

The WSF hotspot analysis reveals Switzerland (orange) and Greece (black) as hotspots of qualitative water use. The Greece hotpot is set to a maximum of 100 and is significantly higher in comparison. This also applies to all hotspots marked in black below, although some are significantly higher and others are only slightly above 100. In Switzerland, the treatment of hard coal ash and the treatment of waste graphical paper and, in Greece, the treatment of lignite ash are responsible for high aluminium emission into water bodies requiring significant virtual dilution volumes. These processes are typical database processes of upstream supply chains in LCA with a good regionalisation for Switzerland and Europe in general. All three processes are part of the operation phase of the coal-fired power plant Heyden. There is no WSF hotspot associated with the construction phase and no WSF hotspot associated with quantitative water use.

Table 3-1: Cumulative LCIA indicator results for case study 1 – the coal-fired power plant Heyden. The share of direct and indirect contributions is given in each case has been provided as percentages. Qualitative and quantitative WSF (WSFquan and WSFqual) in m3 kWh-1, fossil and renewable cumulative energy demand (CEDfo and CEDre) in kWh-Eq. kWh-1, ecosystem damage potential (EDP), ecosystem quality (ECO) and human health (HuHe) in points kWh-1, global warming potential (GWP100) in kg CO2-Eq. kWh-1, raw material input (RMI) and total material requirement (TMR) in kg kWh-1.

	Construction			Operation			Total
	total	direct [%]	indirect [%]	total	direct [%]	indirect [%]	
WSF_{quan}	1.77E-04	0	100	8.54E-03	23	77	8.72E-03
WSF_{qual}	4.24E-02	0	100	1.91E+00	0	100	1.95E+00
CED_{fo}	7.91E-03	0	100	2.79E+00	0	100	2.80E+00
CED_{re}	4.33E-04	0	100	2.87E-02	0	100	2.92E-02
EDP	1.06E-04	40	60	9.54E-03	0	100	9.64E-03
GWP100	2.52E-03	0	100	1.01E+00	89	11	1.01E+00
RMI	7.71E-03	0	100	5.07E-01	0	100	5.14E-01
TMR	1.07E-02	0	100	6.10E-01	0	100	6.20E-01
ECO	5.34E-05	11	89	1.83E-02	86	14	1.83E-02
HuHe	1.71E-04	0	100	3.47E-02	75	25	3.49E-02

Figure 3-2: Hotspot analysis of the indicators WSFquan and WSFqual for case study 1 – the coal-fired power plant Heyden. For each indicator, single process results have been normalised using the median of all case studies. Results have been summarised per location per case study. Values greater than 100 have been set to a maximum value of 100. Any location with a value greater than 50, which equals a medium stress level on the scale from 0 to 100, is considered a hotspot. Global and rest-of-World (RoW) processes are excluded from the analysis. Their share in the total indicator results can be up to 65%. Processes that contribute less than 1% to an indicator result, respectively, are also excluded from the analysis.

3.1.4 Direct and indirect impacts of the energy system on the environment

Looking at the ESA indicators, the fossil cumulative energy demand (CED_{fo}) and global warming potential (GWP100) are especially high during the operation phase of the coal-fired power plant Heyden. CED_{fo} accounts for 2.8 kWh Eq. kWh^{-1}, meaning that almost three times the amount of fossil energy is needed to produce 1 kWh of coal-fired electricity. An analysis of the contributing processes shows that hard coal mining in Russian mines, a supply chain that has been regionalised in the course of the project (Section 2.1.4) and natural gas production in Russia are responsible for 95% of the upstream fossil energy input. The same processes also largely contribute to the ecosystem damage potential (EDP) and global warming potential (GWP100) and damage ecosystem quality (ECO) and human health (HuHe), which reveals the multiple environmental impacts of coal mining. Raw material input (RMI) and total material requirement (TMR) are also relatively high during operation due to the constant material supply of coal. However, the GWP100, ECO and HuHe consist of 75 to 89% direct contributions associated with the last process of the supply chain – the production of electricity on site. The environmental impacts of the construction phase are small in comparison and predominantly remote.

The hotspot analysis reveals on-site hotspots of environmental impacts due to the contributions of the electricity production of the coal plant to the indicators GWP100, ECO and HuHe (black circles around the location of the case study in Figure 3-3a and Figure 3-3b). These stem from the combustion of coal and the associated exhaust gases. Remote hotspots are mostly associated with hard coal mining in Russian mines (circles in Figure 3-3a and Figure 3-3b) and can represent contributions to any of the midpoint ESA indicators. They are often also hotspots of more than one indicator. Further hotspots result from natural gas production in Russia and hardwood forestry in Germany and Sweden (Figure 3-3a). The latter are hotspots of EDP due to land-use changes from forestry.

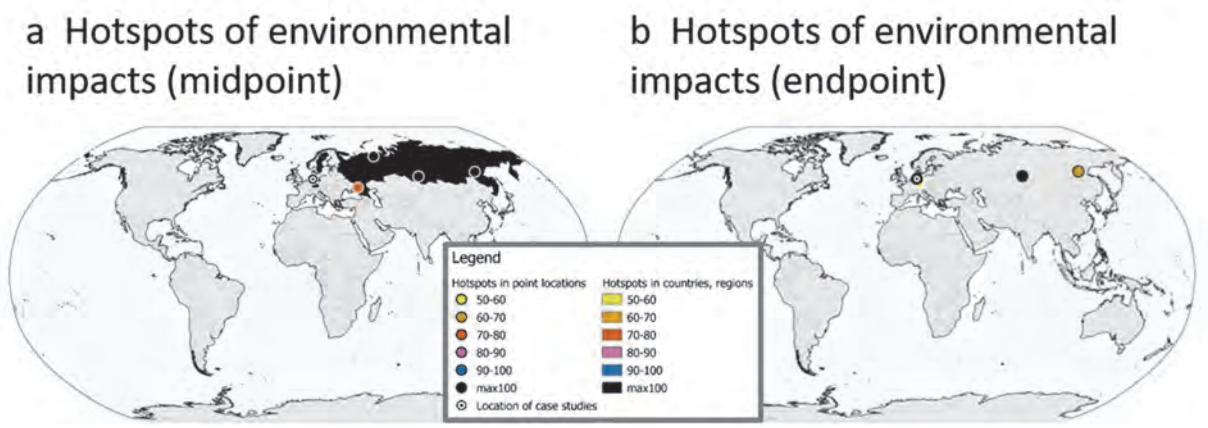

Figure 3-3: Hotspot analysis of the ESA indicators for case study 1 – the coal-fired power plant Heyden. Midpoint environmental impacts (CED, EDP, GWP100, RMI, TMR and WSF) and endpoint environmental impacts (ECO and HuHe) are shown separately (a and b). For further explanations on the hotspot analysis, see Figure 3-2.

The chosen midpoint and endpoint indicators reveal most of the environmental impacts, both on-site and off-site. Nevertheless, two environmental impacts are present that cannot be covered by indicators but need to be explained verbally. The first one affects the landscape and the visibility of the Heyden hard coal-fired power station and originates from virtue of the existence of the power station complex and its infrastructure. The massive buildings, mainly the cooling tower, the boiler house and the chimney that reaches a height of 225 m are visible from far away and therefore have a significant impact on the landscape. The fact that the site is located at the southern fringe of the North German lowlands makes this impact even more significant, as the topography does not hinder visibility. However, it is important to reflect that in this case study, there have been three power blocks on the same site that have been dismantled when block 4 went on stream. These blocks used the same cooling tower and chimney. In conclusion, the Heyden power station already had a significant impact on the landscape before the construction of block 4; thus, the latter did not change the power station's visibility and outward appearance in a decisive way.

The second impact that needs to be discussed is the one on the local flora and fauna. In general, for detailed information on this impact, one needs reliable data, such as maps of on-site vegetation and animals available there before the beginning of construction. Unfortunately, such data does not exist for the Heyden power station. Hence one can only presume that due to the transformation from grassland and groves to a sealed area, various plants and animals lost their habitats. Whether this loss was significant for their population cannot be determined anymore.

3.1.5 Design of instruments to address impacts

The considered system was modelled with the Open Source Real-Time Calculus (RTC) Toolbox developed by Deltares Institute. In Figure 3-4 the river system is schematically illustrated. The gauges at the modelled river sections are pictured as green dots and serve as control points. The inflows to the system are shown as blue arrows meeting at a junction point. The Eder dam and Diemel dam are each shown as a triangle.

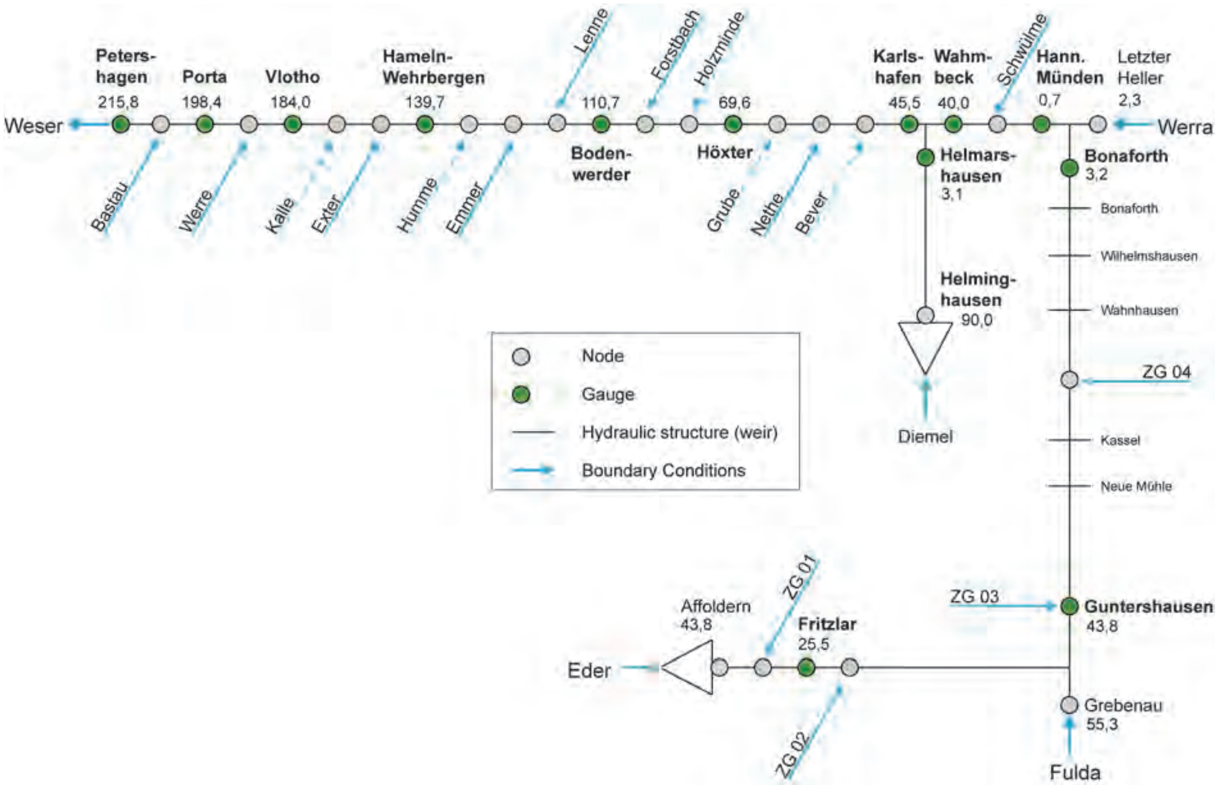

Figure 3-4: Schematic model of the river system – river sections are pictured as green dots and inflows to the system as blue arrows; the Eder dam and Diemel dam are each shown as a triangle.

To balance the filling volume of a reservoir we simplify the general storage equation to the following equation (Eq. 3-1).

$$\frac{dV}{dt} = Q_{in}(t) - Q_{out}(t) \qquad \text{(Eq. 3-1)}$$

A change in the inflow or outflow triggered in a discrete time step accordingly leads to an immediate change in the water level at the dam via the relationship of the storage characteristic curve (assumption of a horizontal water level).

The dam release Q_{out} consists of a controlled, i.e. controllable or optimisable release component $Q_{out,c}$ (control or manipulated variable) as well as an uncontrolled overflow component $Q_{out,u}$ that depends on the storage water level W.

The model predictive control (MPC) is used to determine the best possible (optimised) release strategy for the dams (Figure 3-5). With this regulation, the optimal dam output is determined in a forecast period using predictive state variables and specified targets. The dam release is defined over the calculation period as a sequence of future adjustment steps. The iterative optimisation approach is based on a simulation-supported process model; moreover, based on a prediction time T0, it calculates the effect of a future sequence of correcting variables on the system. This enables an early reaction to future deviations from the target value. The optimisation is based on the principle of minimising the deviation between the model prediction and target specification. The deviation is quantified based on a cost function, which assigns costs to every deviation from the target value. The cost function is made up of several, also opposing, individual goals such as the raise of low flow, flood and navigation, the proportions of which are weighted differently. In addition, secondary conditions such as upper and lower limits or a permissible rate of change can be taken into account. The interior point optimiser (IPOPT) integrated into RTC tools is used for optimisation.

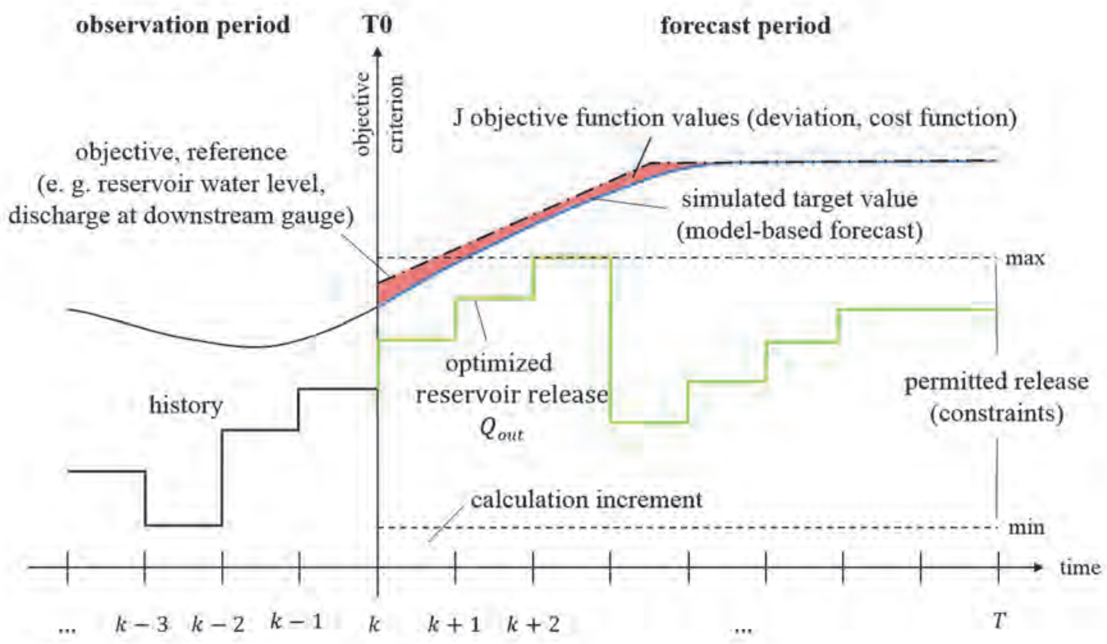

Figure 3-5: Model predictive control (Rötz & Theobald, 2019)

The routing model is used to simulate the flood routing, and in line with forecast and optimisation calculations, it enables the temporal flow characteristics to be identified at selected water stations below the dams. By connecting the reservoir model and routing model, the effects of the dam release become visible, considering translation and retention, up to the Petershagen gauge.

The calculation of the flow processes is based on the maintenance of mass (continuity) and momentum (or energy). The simplified approaches of the complete equation of motion implemented in RTC tools enable the consideration of backwater and hysteresis effects as well as a good approximation to the fully dynamic solution while reducing the numerical solution effort.

For the calculation by the RTC tools, the model area is approximated as a cascade-like series of calculation *nodes* linked by hydraulic connecting elements (*branch*, *hydraulic structure*). The approximately 405 km long stretch of water was modelled using 121 *nodes*, 115 *branches* and 5 *hydraulic structures*.

The calculation of the discharge to the node below in the river system is carried out according to the diffusive wave approach, assuming a representative cross-section for each section of the river. The hydraulic radius is approximated via the average flow depth and the water level gradient is identified via the adjacent nodes. The discharge transfer to the water sections dammed by weir systems is conducted with overflowable structural elements (hydraulic structures). The calculation of the discharge is figured for backflow and free conditions with a simplification of the Poleni formula.

Figure 3-6 presents an overview of the project area with annotated hydrographs at the gauges. The stream gauges are marked as black dots and the dams are represented by blue arrows, as in Figure 3-4. The water course system integrated into the model enables a set point objective at a certain level in the system for optimisation. The shape of the hydrograph can be observed and evaluated across the entire system from the discharge of the particular dam.

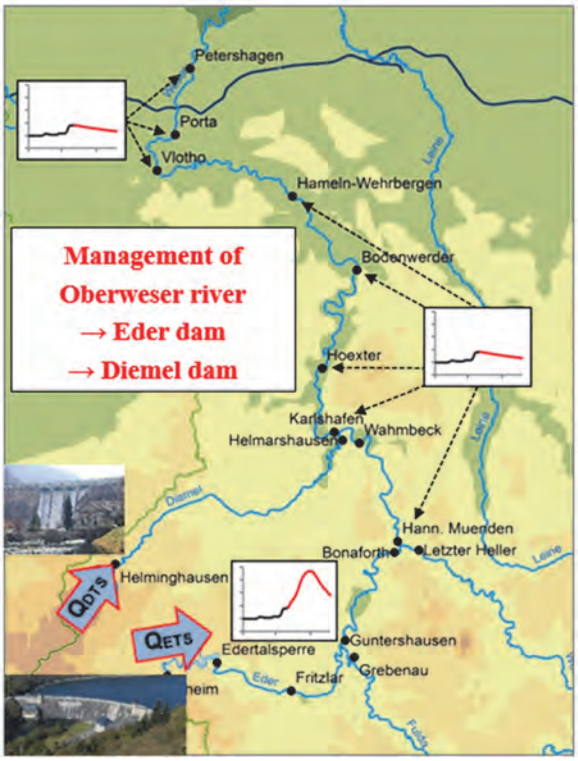

Figure 3-6: Exemplary evaluation of a simulation via the optimisation tool with a cartographic reference of results

In the process of case study 1, the best possible release strategy for the Eder- and Diemel-dams for various management scenarios is to be determined through optimisation. Therefore, simultaneous specifications are made at the Hann. Münden gauge as well as other down-stream gauges on the Oberweser, for example at the Karlshafen or Hameln-Wehrbergen gauges.

According to the operating requirements of the reservoirs, the outflow discharge is identified through an optimisation process. As part of the optimisation, point series objectives or step functions of discharge can be defined, making it possible to specify a discharge for navigation support at a particular water station and at a convenient point in time. Moreover, the different water levels that are to be maintained can be defined at the Weser gauges, which are also part of the optimisation of the reservoir outflow.

In the process of the investigations, calculations for low and mean water discharge as well as for floods were carried out. Short and medium-term time targets were considered, plus different levels of the reservoirs at the beginning of the calculations as well as different requirements at the Petershagen gauge. Additionally, the dam volume was balanced for the different operating cases.

Figure 3-7 shows an example of the evaluation of the optimisation of the reservoir release in accordance with parameters of hydrographs (set point objective) at the Hann. Münden and Karlshafen gauges (blue and red dashed lines). To achieve these requirements, the discharges from the Diemel and Eder dam were identified through optimisation (orange and green lines, secondary y-axis). The interaction of changeable and unchangeable tributaries such as the Fulda or Werra in the river system results in the discharge hydrograph at the observed gauges (blue and red lines). In the internal evaluation of the release strategy as part of the optimisation of RTC tools, the target function can be designed in such a way that exceeding and falling below the target are punished differently. If the level falls below the target, the penalties in the model are ten times higher than if it is exceeded. The target values (dashed lines) are therefore often exceeded and seldom undercut by the optimised hydrographs (solid lines).

Undercutting will be penalised because it does not achieve the required discharge at the gauge and the associated use of the stretch of water can be harmed. Exceeding will also be punished, as exceeding the required dam release over a longer period seriously affects the limited water resources in the reservoirs, which can limit or prevent later use. The setting steps for the dams' releases are each valid for 10 hours before they can be changed again. Due to the constant outflow of the Edertal reservoir within this interval and the superimposition of uncontrolled inflows into the system, the target value is exceeded and undercut. The water levels in the reservoirs and thus the current storage capacities are also part of the optimisation, whereas their upper and lower limit values that are being weighted are so high that they are never exceeded or undercut in the process of optimising the dam's discharge. The output spectrum of the dams is specified as a fixed condition and cannot be ignored. The Eder dam has an output range between 6 m^3/s and 80 m^3/s, while that of the Diemel dam is between 1 m^3/s and 6 m^3/s. The storage capacity of the Eder dam with 200 million m^3 is ten times the volume of the Diemel dam, which means that it can supply the greater part of the required water masses. The Diemel dam supports the Eder dam in achieving the targets through its lower discharge.

Figure 3-7: Evaluation of the optimisation for shipping

Aside from the specification of hydrographs (setpoint series objectives) for enabling navigation on the Weser for a short period, optimisation for raising the low flow over a longer period is also possible. Figure 3-8 displays an evaluation of the rise in the low flow at the Hann. Münden and Hameln-Wehrbergen gauges over four weeks. The discharge specifications at the gauges (dashed) and the simulated, optimised discharge hydrographs (solid lines) are shown in red and blue. To meet the discharging specifications for the gauges over the respective period, the Ederdam emits a volume of 53.6 million m^3 and the Diemeldam a volume of 9.3 million m^3. Based on Figure 3-8, it can be seen that the rise in the low flow is possible over four weeks under the given boundary conditions, with the amount of water released at the Diemel Reservoir corresponding to approx. 46.5% of the total volume and at the Eder dam approx. 26.8% of the storage capacity. Hence, it is possible to raise the low flow level within a limited time, but this will massively reduce the reservoir volume.

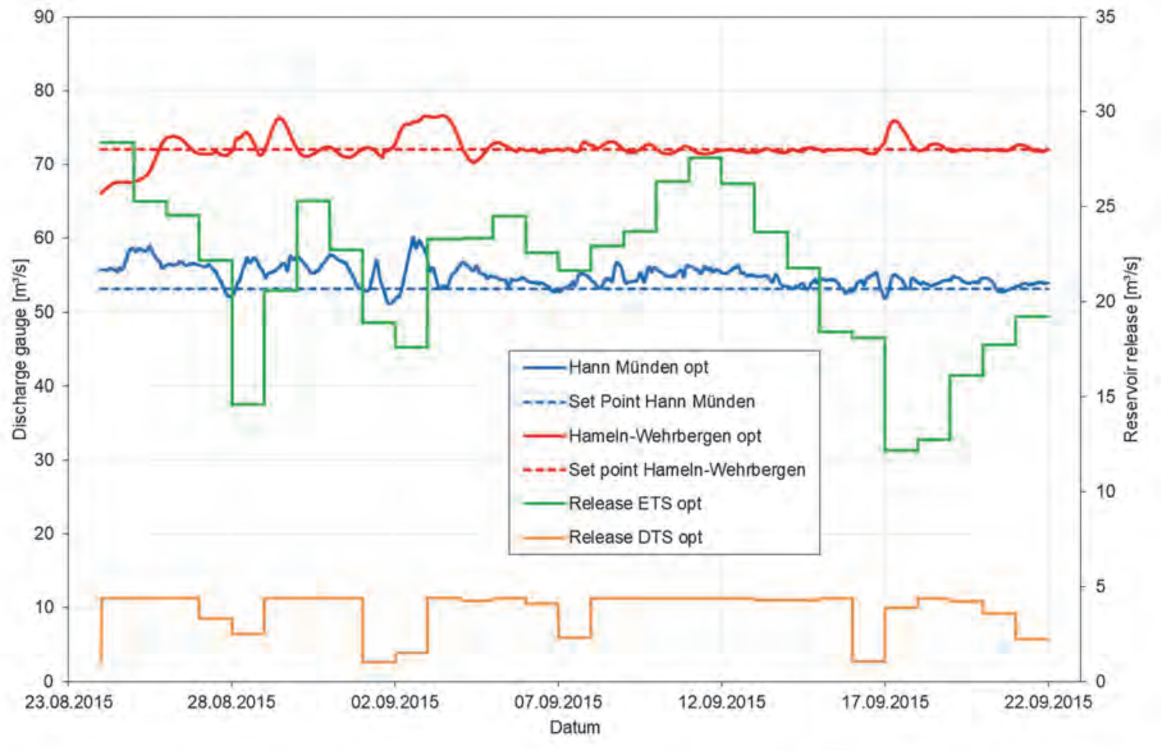

Figure 3-8: Evaluation of the optimisation for low flow conditions

In addition to the scenarios of shipping as well as low and mean water, the effects of water use were analysed against the background of a changed water supply. The balancing of the water consumption at the Mittelland Canal (MLK) and the Heyden power plant was the focus.

Figure 3-9 illustrates the location of the Heyden power plant, MLK and the Petershagen gauge. The mean low water discharge (MNQ summer) at the Porta gauge is 76.5 m³/s.

The Heyden coal-fired power station takes cooling water from the Weser at an average of 1.87 m³/s via a discharge section, with the re-charge at Q = 1.75 m³/s. The supply can therefore be estimated as rather uncritical. As the Heyden power plant is to be shut down in the course of the German phaseout from coal-fired power, it can be neglected while considering the future water supply.

The quantity of water that can be withdrawn for the MLK from the Weser is currently a maximum of approx. 8 m³/s; in the future, this may increase due to climate change and potential changes in the requirements of the technical infrastructure. This could become particularly critical in periods of low water, especially in the case of greater future demand and lower supply in the summer months (low water period).

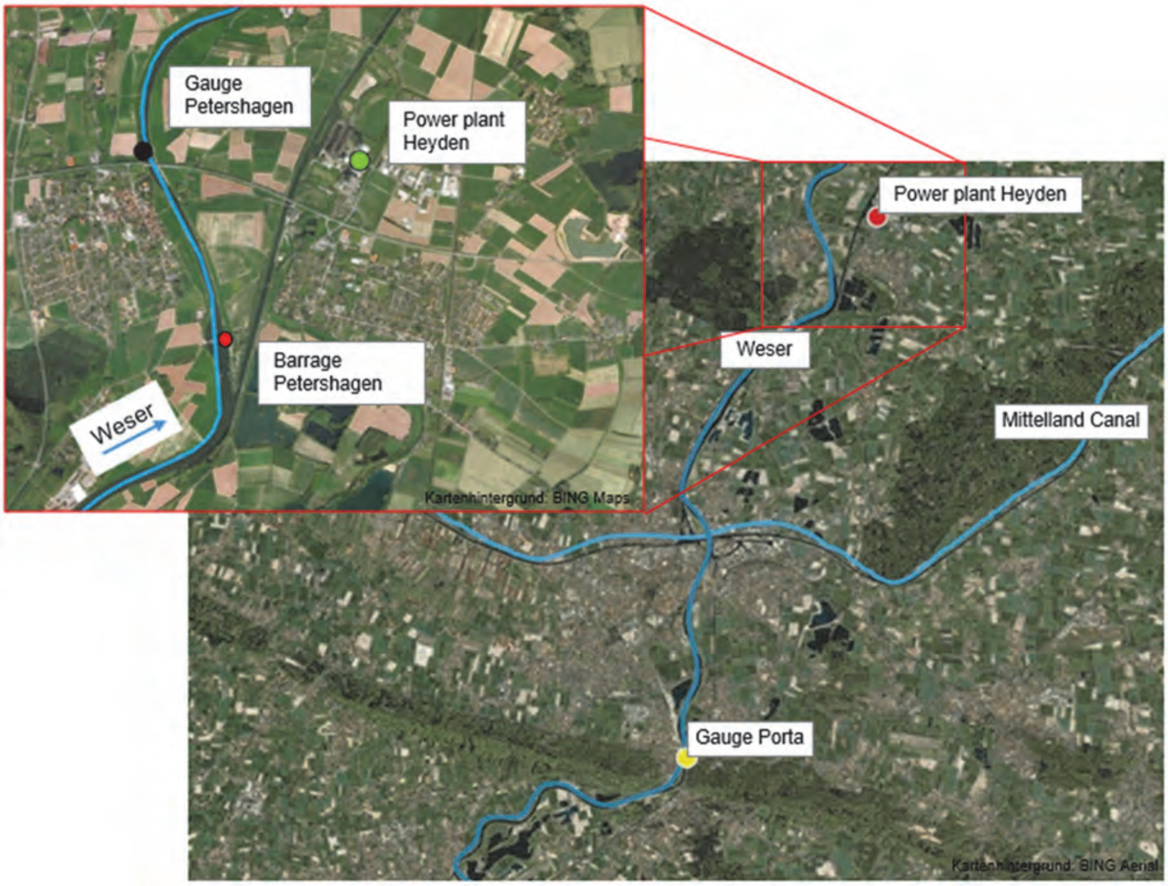

Figure 3-9: Power plant Heyden and Mittelland Canal (MLK)

3.2 Cascade of Six Hydropower Plants on River Danube, Germany

Authors: Swantje Dettmann, Sarah Dickel, Tobias Vogtmann, Stephan Theobald, Anna Schomberg, Martin Kondring, Dirk Menker, Andreas Boyer

3.2.1 General overview of the case study

As per the scope of case study 2, the Department of Hydraulic Engineering and Water Resources Management at the University of Kassel analysed the potential of improved electricity generation strategies for a cascade of hydropower plants. Furthermore, in cooperation with KIMA GmbH, the simulation model used was transformed into a training simulator for the operating staff of the control room.

The investigation area comprises the cascade of the six hydropower plants on the upper Danube (ODK) from Oberelchingen to Faimingen and extends from Danube-km 2581.5 (barrage Böfinger Halde, inflow into the reach Oberelchingen) to Danube-km 2545.3 (barrage Faimingen). The location of the dams plus a scheme of dams with local controllers are illustrated in Figure 3-10. The installed power generation capacity of the hydropower plants ranges between P = 7.4 MW and P = 10.1 MW, and the total capacity of the cascade is P_{total} = 52.5 MW.

The analysis carried out in case study 2 not only aimed at maximising the generation of electricity, but also analysed the possibilities for providing more complex and therefore higher remunerated electricity products. In contrast to many other electricity generation technologies, hydropower is most versatile and can be used to cover both, base load and peak load. Furthermore, it can provide a control power range to support the frequency of the grid (see Section 5.3).

In addition, case study 2 also aimed at augmenting the simulation system to make it a user-friendly tool that can be used as a training system by the control room staff. For that purpose, KIMA GmbH, in cooperation with the Department of Hydraulic Engineering and Water Resources Management linked the simulation model to a copy of the control structures and user interfaces of the control room, which is illustrated in detail in Section 5.4.

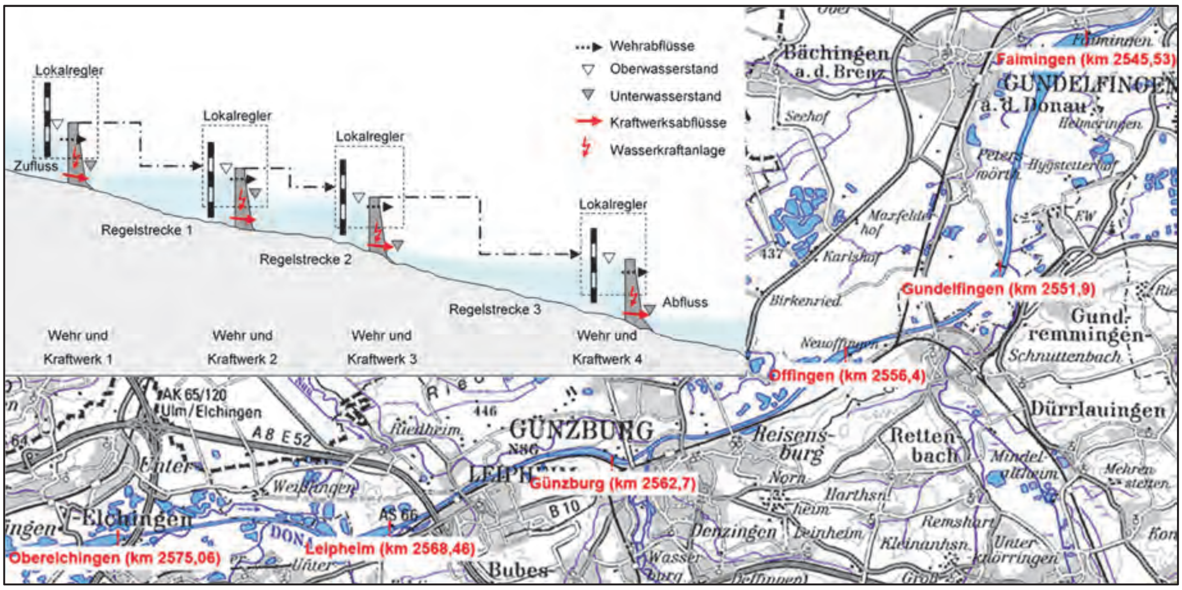

Figure 3-10: Location of the dams and (inset) a cascade of hydropower plants with local controllers

3.2.2 Energy system

Hydropower is one of the most important and most intensively used sources of renewable energy worldwide. In 2018, its share of the world's electricity supply was about 15.9%, which represents 58.2% of the electricity generated from renewable energy sources (see Figure 3-11). Since 1990, the electric energy generated from hydropower in Germany has been between about 17 TWh/a (1998) and 23 TWh/a (2002) – which corresponds to a share of 2.8 to 4% of total production (BMWi, 2019) – with the range mainly reflecting the annual variation of runoff. In other countries, hydropower is the main source of electric energy: in Austria, for example, the share of electricity generated from hydropower is approximately 67%, and in Norway, it is even 99%.

The six hydropower plants of the ODK are located in the districts of Neu-Ulm, Günzburg and Dillingen in the Bavarian administrative district of Swabia. The annual electricity demand of these three districts is approx. 2,600 million kWh (EZA, 2021; Landkreis Günzburg, 2015; B.A.U.M. Consult GmbH, 2013). They generate electricity of approx. 300 million kWh annually, which covers approx. 12% of the districts' needs (LEW, 2021). Around 400,000 people live in these three districts. With an average electricity consumption of approx. 1500 kWh/(pers. * A) (estimate based on data from the Federal Environment Agency (Umweltbundesamt, 2021)), approx. 50% of the residents' electricity needs can be covered by the six hydropower plants.

Around 11.9 billion kWh of the annually produced electricity in Bavaria is generated from hydropower, which corresponds to 15.9% of the electricity generated in Bavaria (Bayerisches Staatsministerium für Wirtschaft, Landesentwicklung und Energie, 2021). After Germany's phasing out of nuclear power by 2022, hydropower in electricity generation will become increasingly important (Bundesregierung, 2021).

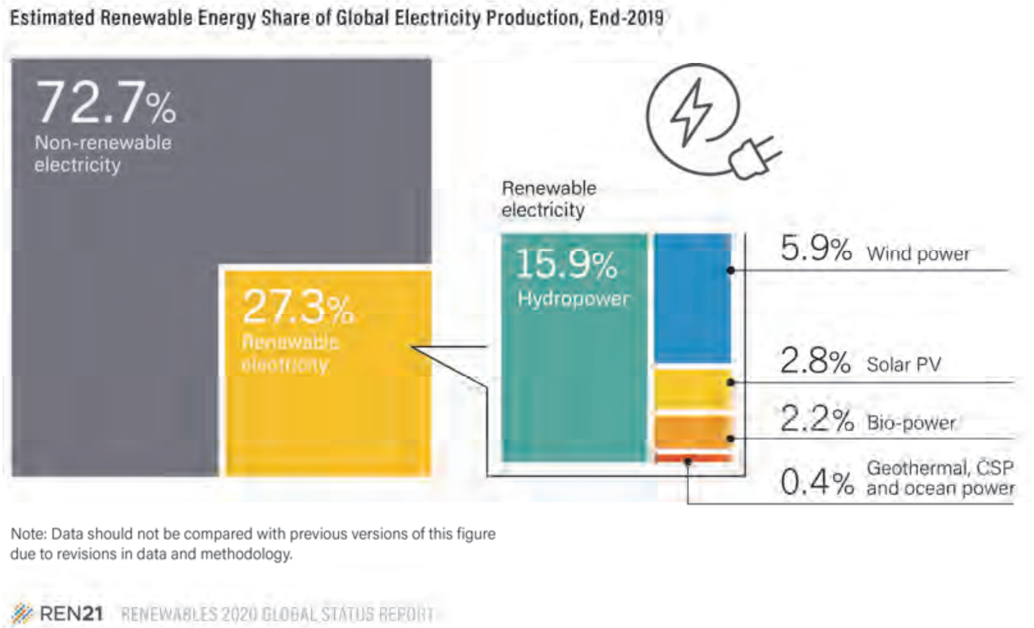

Figure 3-11: Power generation worldwide (REN21, 2020)

An important factor for evaluating the different technologies for electricity generation is the emission of the greenhouse gas CO_2, particularly with regard to climate protection. Compared to other electricity generation technologies, the emission of greenhouse gas caused by hydropower generation is very low (Köhler et al., 2020). The specific greenhouse gas emission (given in g CO_2 equivalent per kilowatt-hour) of the different technologies was determined by an LCA considering the production of the plant components, transport, installation (plant construction), operation and recycling/dismantling of the plants, thus spanning the entire life cycle of the plant. The results, which are shown in Figure 3-12, demonstrate the advantage of hydropower over the other regenerative technologies. While the greenhouse gas emission of hydropower is between 0 g and 11 g CO_2eq/kWh, for biomass, it is up to 172 g CO_2eq/kWh. For wind energy, the range is between 39 g and 106 g CO_2eq/kWh and for photovoltaics between 50 g and 67 g CO_2eq/kWh. Electricity generation from fossil fuels emits greenhouse gas far above the maximum value for hydropower. Using these numbers, it can be calculated that in Germany, for example, in 2018, with an annual production of 19.4 TWh from hydropower, approximately 30 million tons of CO_2eq. could have been saved compared to electricity production from lignite.

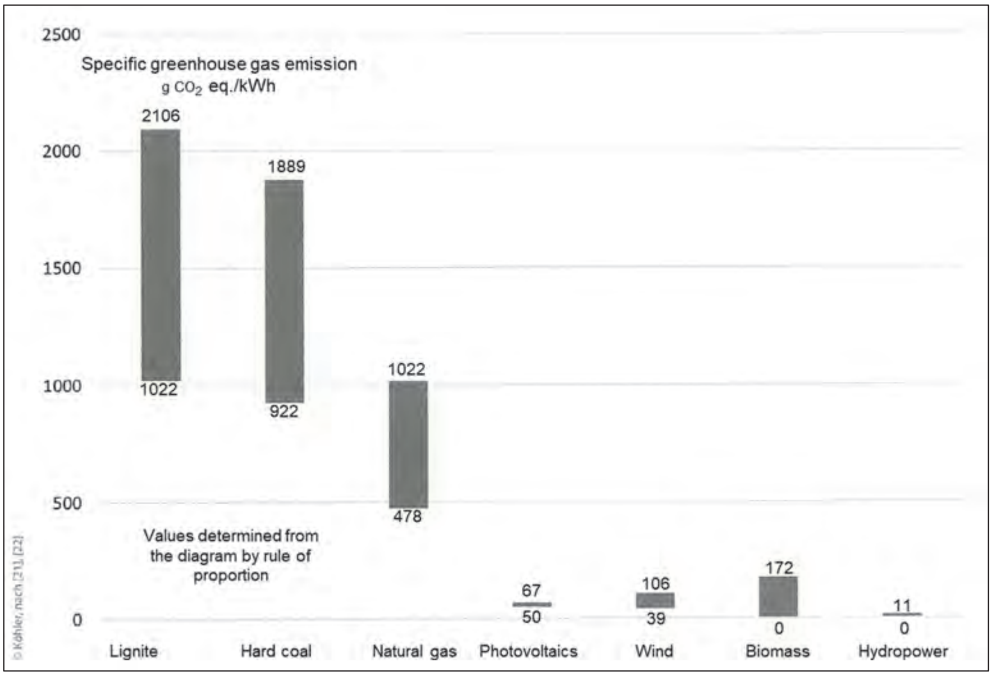

Figure 3-12: Specific greenhouse gas emissions from various power generation technologies (Köhler et al., 2020)

The generation of approx. 300 million kWh/a by a cascade of hydropower plants produces approx. 1,630 t CO_2 eq each year. If the same amount of energy were generated by biomass, approx. 25,500 t CO_2 eq would be produced annually, with the use of photovoltaics approx. 17,400 t CO_2 eq and by using hard coal approx. 417,500 t CO_2 eq. Thus, using hydropower leads to annual savings of approx. 24,000 t CO_2 eq compared to the use of biomass, approx. 16,000 t CO_2 eq compared to the use of photovoltaics, and approx. 416,000 t CO_2 eq compared to the use of hard coal. As part of the German climate protection policy, initially, greenhouse gas emissions are to be gradually reduced. By 2050, greenhouse gas neutrality is supposed to be achieved (Bundesministerium für Wirtschaft und Energie, 2021). With its comparatively low emission of CO_2 equivalents, using hydropower will greatly contribute to achieving this goal.

Another important criterion for comparing different power generation technologies is the energy return on energy invested (EROI or ERoEI), which shows the ratio of energy generated (MJ_{el}) over energy used (MJ_{PE}) during the entire life cycle of a plant. In a study carried out at the ETH Zurich, this was compared in detail for various electricity generation technologies (see Figure 3-13). The results of this study clearly show the advantage of hydropower over conventional electricity production and over other regenerative technologies. The EROI of conventional technologies ranges from 3 MJ_{el}/MJ_{PE} for gas up to 12 MJ_{el}/MJ_{PE} for nuclear power. Of the regenerative energy sources, geothermal energy with an EROI of

3 MJ_{el}/MJ_{PE} is at the lower end of the scale, and the EROI of photovoltaics ranges between 4 and 8 MJ_{el}/MJ_{PE} and of wind power between 18 and 20 MJ_{el}/MJ_{PE}. The results for hydropower are significantly higher: for reservoir hydropower, the EROI is 58 MJ_{el}/MJ_{PE}, and for run-of-river hydropower, it even reaches 78 MJ_{el}/MJ_{PE}.

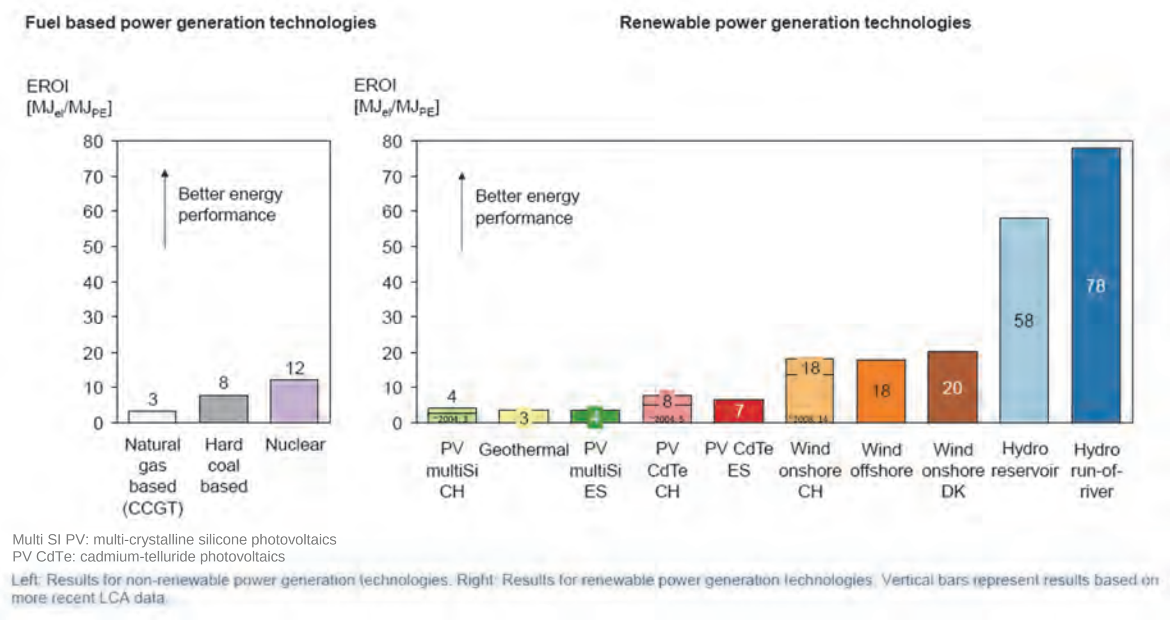

Figure 3-13: EROI for various power generating technologies (Steffen et al., 2018)

For generating approx. 300 million kWh/a via run-of-river hydropower plants, with a ratio of energy generated to energy required of MJel/MJPE = 78 (see Figure 3-13), approx. 3.8 million kWh is required per year. Based on a term of 80 years, around 300 GWh is required to generate 23,760 GWh of electricity. To generate the same amount of electricity from photovoltaics, approx. 4,100 GWh is required and from hard coal approx. 3,000 GWh. The use of hydropower thus enables electricity to be generated with a comparatively low primary energy requirement.

In conclusion, hydropower is a very advantageous form of electricity generation, both in terms of CO_2 emissions (and thus climate protection) and EROI. This is one of the reasons for hydropower plants being built in many countries around the world, e.g. in South America, Asia and Africa. Unlike most other power generation technologies, hydropower is suitable for generating baseload and peak power and providing control power for grid stabilisation, as described in Section 5.3.2.3. However, hydropower is dependent on specific geographical conditions and therefore cannot be expanded at will, which makes the upgrading and modernisation of existing plants, equipment and regulation strategies very important.

3.2.3 Direct impacts of the energy system on water resources

The total WSF_{quan} of the hydropower plants at the Danube is 0.02 m3 kWh-1 with most of it associated with the operation phase (Table 3-2). The contributions of the operation phase are 100% direct and are associated with evaporation losses from the river due to impoundment areas (for details of the calculation, see Appendix A). This also appears as an on-site hotspot of the WSF of the Danube hydropower plants (pink circle around the case study location in Figure 3-11). With approximately 3.4 m^3 kWh^{-1}, the total WSF_{qual} is significantly higher; additionally, most of it can be attributed to the construction phase (Table 3-2). The contributions are 100% remote and will be described further in the next section.

3.2.4 Indirect impacts of the energy system on water resources

Apart from the WSF_{quan} of the operation phase, all other contributions to the WSF come from the upstream supply chain (Table 3-2) and are therefore associated with indirect impacts. The WSF_{quan} of the construction phase is related to upstream processes that provide materials, such as hard coal, steel, lime or iron, and electricity for the upstream supply chain. However, it is minimal compared to the WSF_{quan} of the operation phase. In contrast, with 3.4 m^3 kWh^{-1}, the WSF_{qual} of the construction phase is high, compared to the coal-fired power plant. This is most likely an effect of the conversion to 1 kWh taking into account the energy yield: the annual energy production of the coal-fired power plant over its lifetime is significantly greater compared to its construction effort, which is why the environmental impact of the construction phase per kWh is lower. Treatment of inert waste in Europe is responsible for over 97% of the contribution to WSF_{qual} due to its high aluminium emissions. It is part of the upstream chain and only indirectly linked to the case study. To identify the relevance of this particular process for the case study and, especially, possibilities for reducing the high WSF_{qual}, more in-depth analyses are necessary.

The WSF hotspot analysis identifies exactly this process as hotspot of qualitative water use due to the construction of the Danube hydropower plants (Figure 3-14), thus also indicating that further analyses are required here.

Table 3-2: Cumulative LCIA indicator results for case study 2 – run-of-river hydropower at the Danube. For further explanations, see the caption of Table 3-1.

	Construction			Operation			Total
	total	direct [%]	indirect [%]	total	direct [%]	indirect [%]	
WSF_{quan}	9.64E-04	0	100	1.54E-02	100	0	1.63E-02
WSF_{qual}	3.42E+00	0	100	1.34E-04	0	100	3.42E+00
CED_{fo}	5.36E-02	0	100	2.36E-04	0	100	5.39E-02
CED_{re}	3.36E-03	0	100	1.05E+00	100	0	1.06E+00
EDP	4.33E-04	0	100	5.18E-07	0	100	4.34E-04
GWP100	1.87E-02	0	100	3.89E-05	0	100	1.87E-02
RMI	1.04E-01	0	100	2.71E-05	0	100	1.04E-01
TMR	1.20E-01	0	100	3.45E-05	0	100	1.20E-01
ECO	3.54E-04	0	100	7.03E-07	0	100	3.55E-04
HuHe	1.18E-03	0	100	1.75E-06	0	100	1.18E-03

Figure 3-14: Hotspot analysis of the indicators WSFquan and WSFqual for case study 2 – run-of-river hydropower at the Danube. Further explanations, see the caption of Figure 3-2.

3.2.5 Direct and indirect impacts of the energy system on the environment

Looking at the ESA indicators, only CED_{re} reveals direct impacts. In this case, the indicator does not highlight any environmental impact but summarises the energy from the water that is used to generate electricity. If this indicator has no indirect contributions, it is of interest if several identical case studies are to be compared in terms of their efficiency. For the construction phase, it is noticeable that the indicator results of GWP100, RMI, TMR, ECO and HuHe, all of which are almost exclusively associated with the production of construction materials or energy in the upstream supply, are one order of magnitude greater than those of the coal plant. This is again due to the effect of conversion to the functional unit of 1 kWh. In contrast, the contributions from the operation phase are very small, as the operation of a hydropower plant requires very little input.

The ESA hotspot analysis shows only one hotspot associated with the Danube hydropower plants (Figure 3-15a, black circle around location of the case study), which comes from the indicator CED_{re}. As already described, this is not a hotspot of environmental impacts, but can be relevant in other comparative analyses.

As the run-of-river hydropower at the Danube does not require continuous resource inputs, the described indicator and hotspot analysis does not show any significant environmental impact related to the dam's operation. Nevertheless, there are severe ecological impacts caused by the pure existence of the six dams. These impacts could be recorded and evaluated using various indicators, but for comparing the impacts of a barrage with three non-hydropower-based forms of energy production, such an evaluation is inadequate. Instead, these case study-specific impacts are to be presented verbally and argumentatively and contrasted with the identified advantages of hydropower utilisation.

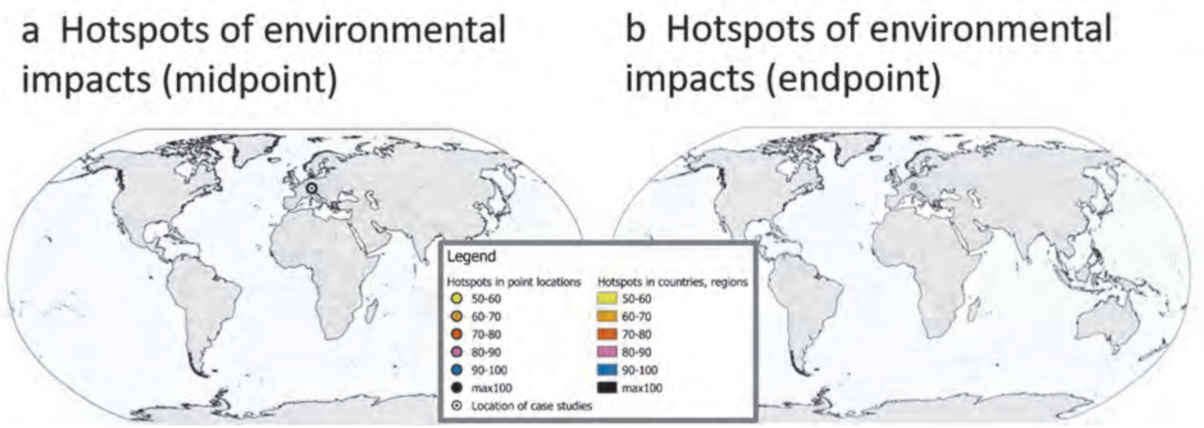

Figure 3-15: Hotspot analysis of the ESA indicators for case study 2 – run-of-river hydropower at the Danube. Midpoint environmental impacts (CED, EDP, GWP100, RMI, TMR, WSF) and endpoint environmental impacts (ECO, HuHe) are shown separately (a and b). For further explanations, Figure 3's caption. The analysis reveals only one hotspot (a), directly at the location of the case study.

The regulation of the Danube river started in the early 19th century and led to a deepening of the river by several metres and a drawdown of the ground-water level by up to three metres. The construction of dams on both sides of the river and the regulation of the Donau's tributaries started in 1890. The construction of the barrages regarded in this case study took place between 1961 and 1984. It stopped the groundwater drawback but, on the other hand, reduced the frequency of natural flooding events. In consequence of the latter, the riparian forest ecosystem began to change and species adapted to riparian ecosystems began to become endangered or disappear (Kling Consult, 2012). What is more, there is no doubt that the run-of-river hydropower at the Danube did and still does alter the river's natural flow regime and impedes its nutrient and sediment transport (Maavara et al., 2020). Besides, the damming leads to an increase in water temperature and thus to a reduction in the water's oxygen level. This not only increases the greenhouse gas emissions from the water (Guérin et al., 2006) but also changes the composition of freshwater species. The latter effect is enhanced by the fact that dams block movement pathways of fish and other freshwater species.

As stated above, the regulation of the Danube river started about 150 years before the construction of the barrages. Historical maps show how the riparian landscape dramatically changed due to riverbank stabilisation and a shortening of the river by several kilometres. As a result, the construction of the six contemplated barrages in the second half of the 20th century did not change the landscape as much as the preceding human impacts did. The transverse barrages and the turbine housing are visible from along the river and within the Danube valley only. In contrast, they cannot be seen from nearby villages and towns. Thus, the impact on the landscape can be looked upon as minor and negligible.

3.2.6 Design of instruments to address impacts

3.2.6.1 Outline

The aim of case study 2 was to set up a simulation tool for analytical investigations concerning the operation and generation of power in a cascade of hydropower plants and create a user-friendly tool to be used by the control room staff on site for training purposes.

Hydrodynamic-numerical models of the individual reaches of the upper Danube hydropower plants, including the feedforward controls installed on site, already existed at the Department of Hydraulic Engineering and Water Resources Management at the University of Kassel and could be combined and complemented by modules for energy production. Like the hydraulic state of the river system itself, hydraulic energy production is a highly dynamic process. Therefore, it is necessary to link energy calculation approaches, control procedures and numerical methods to provide a comprehensive model of the hydraulic system with a high temporal resolution and in detail (Theobald, 1999).

In the one-dimensional (1D) hydrodynamic numerical (HN) method used in this study, the one-dimensional Saint-Venant equations are solved using the finite difference scheme first introduced by Preissmann (1961). The programme calculates time-dependent water depths, discharge rates and velocities averaged over the wetted area, thus permitting analyses of the unsteady flow within the reaches.

The investigated reach of the upper Danube is described in Section 3.2.1. Its total length of approx. 36 km is mapped by cross-sections with a distance of 200 m. As the main parameters for determining power generation – discharge and water head – are time-dependent, it is necessary to consider these parameters in a high-resolution time grid. They are calculated by the HN-method for each time step and used directly for evaluating the generated power. The power generation module comprises technical parameters, such as the efficiency of the generator and transmission as well as hydraulic losses. In accordance with their individual maximum discharge, the total discharge is distributed to the turbines and used to determine the total generated power of the plant, considering admissions and efficiencies (Rötz, 2013). Hydroelectricity is a highly flexible mode of power production. Due to the versatile possible operation strategies of hydropower plants, the priority for electricity generation from hydropower is not, necessarily, maximising the total output for baseload coverage. This study focuses on other aspects, such as controlling the timing of power generation in order to cover the peaking power demand or stabilise the frequency of the power grid. As this cannot be offered by many power generation technologies, it is of particular interest and often remunerated well. The study's findings on electricity generation are described in Sections 3.2.6.2 and 3.2.6.3.

To make the system usable for operators on site and the control room staff, a training simulator was developed jointly by the company KIMA GmbH (KIMA) and the Department of Hydraulic Engineering and Water Resources Management at the University of Kassel. It consists of the HN model and the original control structures and interfaces implemented by

KIMA on software-PLC, plus a newly designed user interface for the overall system (see Section 5.3). Attention was paid to maintaining all operating and configuration options of the original system both functionally and visually as far as possible. The aim was to offer the user a 'look and feel' of the real system. Only an additional user interface for the settings of the training simulator (such as the choice of inflow hydrograph, time lapse, start/stop, etc.) had to be created.

The intent behind the development of the training simulator is to provide an instruction and practice tool for operators of the hydropower plants and thus a training environment for the simulation of normal operation as well as hand interventions and incidents. It can be used for optimisation as well as for testing and demonstration. Details about the training simulator can be found in Section 3.2.6.4.

3.2.6.2 Increasing electricity production

To increase the electricity production of run-of-river hydropower plants, an increase in the discharge and/or water head (difference between the upper and the lower water level at the barrage) is necessary. The latter can primarily be adjusted by raising the headwater level at the barrage, which, however, would conflict with the target water level specified in the concession. To evaluate the effect of a (theoretical) change in the target water level on the total electricity production, simulations with different head water levels were compared. Additionally, after an investigation, electricity production with a smoothed discharge (compared to the inflow) was found to have a positive effect on the water course in general as well as on the wear of the regulators at the downstream plants.

Figure 3-16 shows an example of this investigation based on a discharge hydrograph recorded in July 2016. The inflow into the first reach, which is the discharge at the barrage of Böfinger Halde, is indicated by the black line. For the simulation with feedforward controls in operation at all of the barrages, the discharge at the downstream end of the cascade, which is at the Faimingen barrage, is marked in blue. For a smoothed discharge scheme, the discharge in Faimingen is indicated by the red line.

Figure 3-17 shows the total power output for the scenarios described above. The yellow line indicates a regular case where the target water level defined in the concessions is maintained. The red and green lines indicate the total power output for a permanent increase or decrease in the target water level by $\Delta z = 15$ cm respectively. For the smoothed discharge scheme, indicated by the blue line, the total power output turns out to be more uniform, while the total output over time does not change compared to the total output over time in the normal operation mode. On the other hand, a change in the target water level by $\Delta z = \pm 15$ cm does change the total power output: it is increased or decreased by approx. ±1% (when $Q \approx 100$ m³/s) until by up to approx. ±1.8% (when $Q \approx 210$ m³/s, which is the maximum discharge of the turbines).

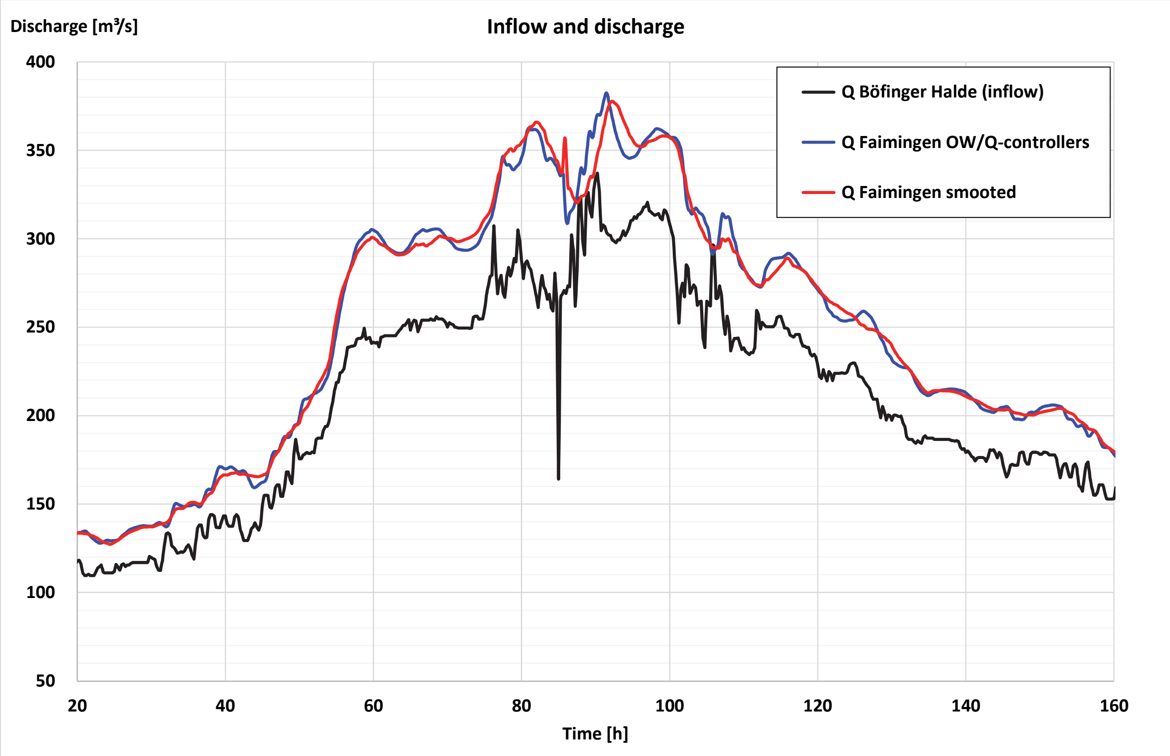

Figure 3-16: Inflow and discharge hydrograph

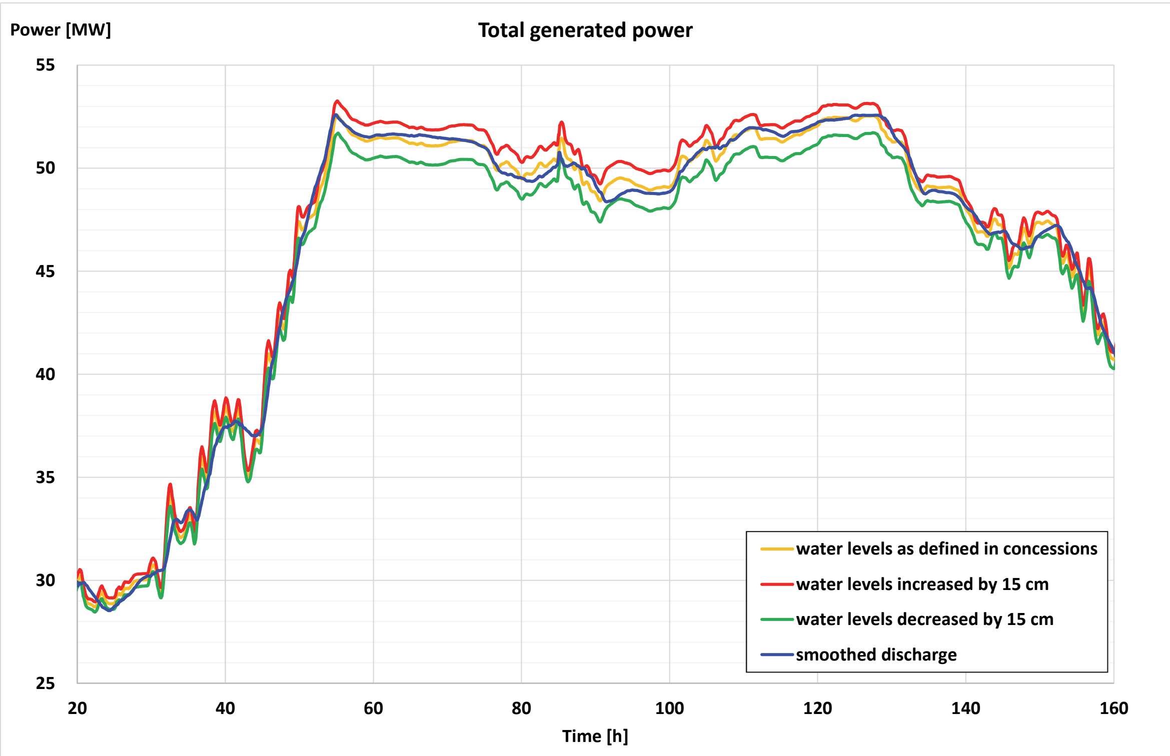

Figure 3-17: Total generated power

3.2.6.3 Control reserve

A permanent balance between electricity generation and demand is an important precondition for the stable and reliable operation of the electrical grid. Differences between feed-in and consumption need to be compensated by activating the control reserve with the objective of, on the one hand, maintaining the system frequency within a narrow range around its target frequency of 50 Hz and, on the other hand, eliminating regional deviations in the balance from their reference value. For this purpose, different types of control reserve have to be deployed, mainly distinguished by their activation time span and their maximum deployment time (see Figure 3-18).

In run-of-river hydropower plants, negative control reserve can be provided by shifting discharge from the turbines to the weirs and thus producing less or no energy without causing much impact on the water balance. Only the different opening speeds of the turbines and the weirs can lead to short-term fluctuations in discharge. However, considering the capacity provided, a better alternative would be to temporarily retain this water by allowing the water level to rise and then use it for power generation when the natural inflow is lower. Positive control reserve can be provided by temporarily increasing the discharge, but this reduces the water level in the reservoir and is therefore limited in time. It also affects the water balance in the downstream reaches.

Figure 3-18: Types of control reserve, time given in minutes, figure taken from 50Hertz Transmission GmbH et al. (2020)

Given the cascade of hydropower plants where the head and end reservoirs can be used for storing larger amounts of water, special operating modes can be implemented to temporarily alter electricity generation. Two different strategies were examined in the study: simultaneous hydropeaking and non-simultaneous hydropeaking.

In simultaneous hydropeaking, for a desired increase in power generation, all dams except the last one simultaneously increase the discharge, which provokes a simultaneous increase in power generation and a decrease in the water level at these plants. The discharge at the end reservoir, in contrast, equals the inflow into the first reach of the cascade (possibly increased by the discharge from lateral inflows) and thus compensates for the man-made alteration of the hydrograph by allowing the water level to rise. In the case of a desired decrease in power generation, the directions are inverted, i.e. the discharges in the first five reservoirs decrease and the water levels rise temporarily. In simultaneous hydropeaking, the power generation at all plants either increases or decreases simultaneously; thus, the total alteration of the generated power of the cascade is fully accomplished within the time interval specified (ramping time).

In non-simultaneous hydropeaking, only the discharge – and thus the generated power – at the head reservoir is manipulated. The subsequent reservoirs react to the change in inflow via their controllers and therefore adjust their discharge according to their operational goals, which normally means maintaining a constant headwater level. This, of course, also implies a change in generated power due to the manipulated discharge upstream, but other than in simultaneous hydropeaking, the reaction here depends on the runtime or retention time in the reservoirs. Only at the end reservoir, just like in simultaneous hydropeaking, is the manual intervention compensated by letting the water level vary so that the discharge at the end reservoir can equal the inflow into the first reach of the cascade (possibly increased by the discharge from lateral inflows).

In non-simultaneous hydropeaking, the time interval for changing the generated power is therefore only definable for the first hydropower plant. All subsequent plants react according to their particular controller settings. For the cascade on the upper Danube with six hydropower plants, this means that the maximum or minimum total change in generated power is reached after approx. 35 minutes.

Figure 3-19 to Figure 3-21 illustrate the power generated through simulations with a constant inflow of $Q = 170$ m³/s and an increase in discharge or later decrease of $\Delta Q = 20$ m³/s within 30 s for simultaneous and non-simultaneous hydropeaking. Just like in reality, the model works with headwater/discharge-controllers (OW/Q-controllers) at all plants, a closed loop level control with feedforward of the inflow to the controller output (discharge).

Figure 3-19 shows a detail of the graph for the generated power where the coloured lines mark the generated power at the individual plants and the black line stands for the total generated power of the cascade. For simultaneous hydropeaking, as can be seen in the left diagram, the entire increase in total generated power occurs in the selected period. In contrast, in non-simultaneous hydropeaking, the immediate increase in generated power only occurs at the first dam; the following gradual increase in generated power at the subsequent plants is a consequence of the increasing discharge and the reactions of local controllers. Figure 3-20 shows the graphs of the generated power for the entire duration of the simulation.

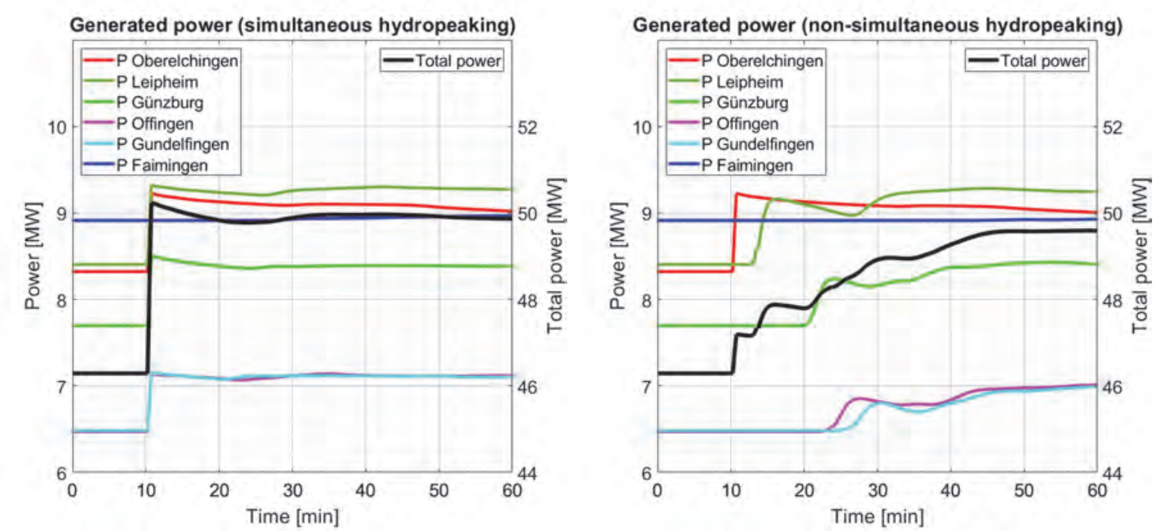

Figure 3-19: Power generation in simultaneous and non-simultaneous hydropeaking (details)

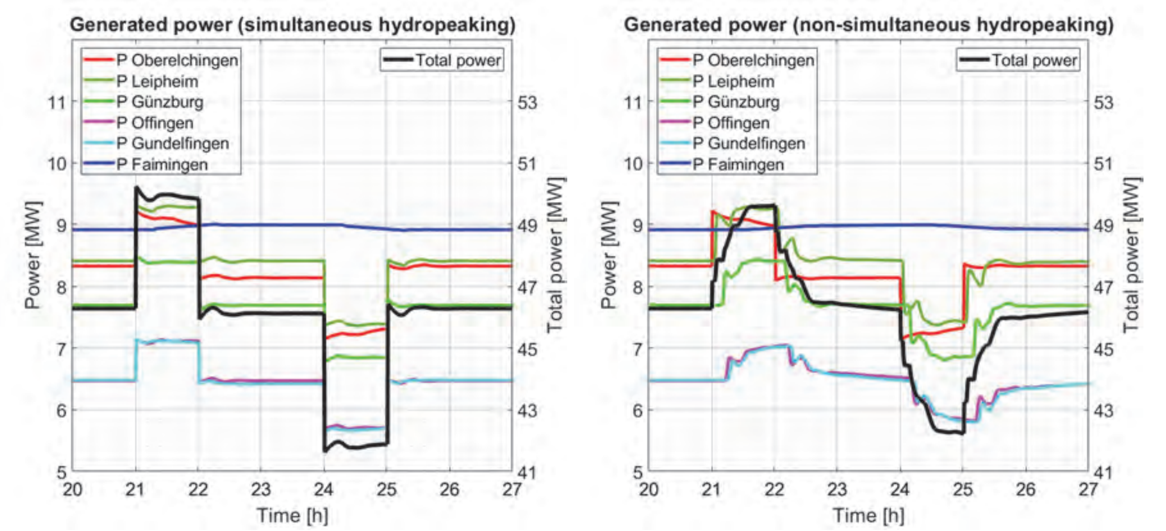

Figure 3-20:Power generation in simultaneous and non-simultaneous hydropeaking

Figure 3-21 illustrates the water level development in the particular reservoirs for the above hydropeaking modes. The blue line shows the result of simultaneous hydropeaking, the red line for non-simultaneous hydropeaking. The order of magnitude of the water level development is the same in the top and end reservoirs. The deviation from the target value is small in the middle reservoirs. In non-simultaneous hydropeaking, it normally recedes completely, while in simultaneous hydropeaking, a deviation of a few centimetres remains for the duration of the altered discharge.

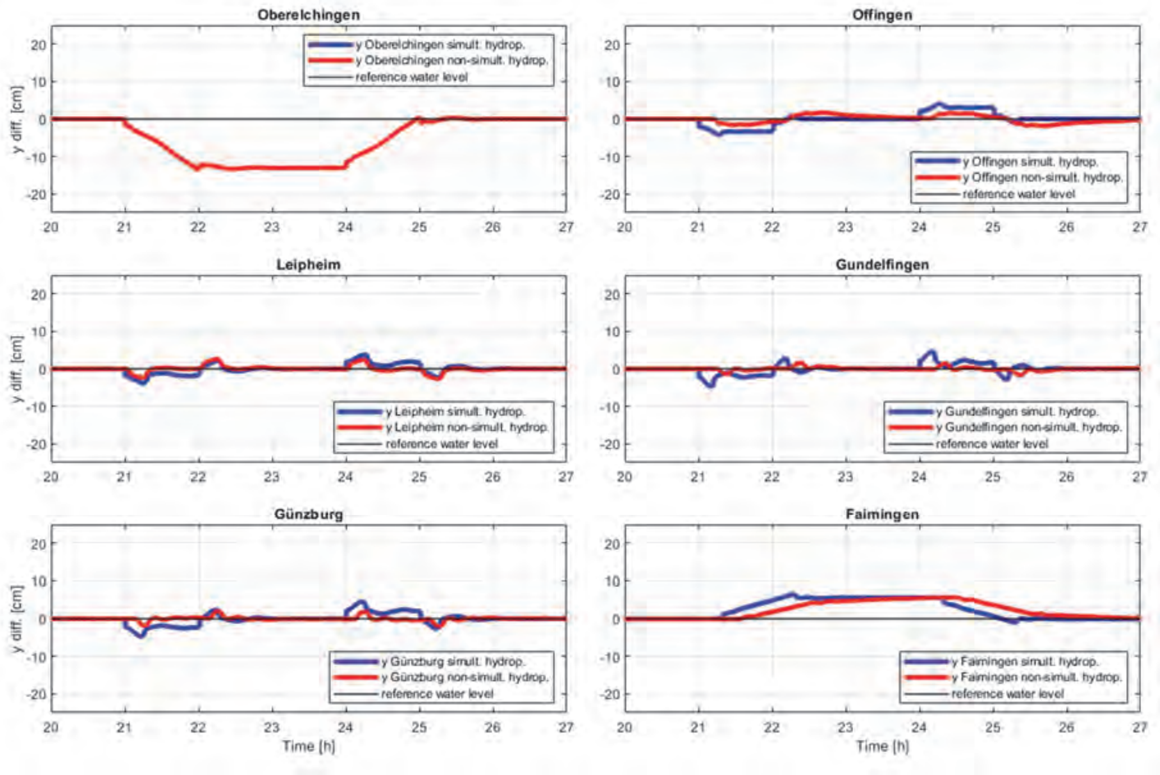

Figure 3-21: Water level development in simultaneous and non-simultaneous hydropeaking

It should be noted that run-of-river hydropower plants can be used to stabilise the frequency of the electrical grid through targeted intervention in their electricity generation. Negative control reserve, if required, can be achieved without interfering with the water balance by discharging water via the weirs instead of the turbines. Alternatively, the excess water (not used for power generation) can be retained by temporarily raising the headwater level and processing it later, given that there is sufficient capacity in the reservoirs.

As the abovementioned results for the power generated over time show, all six plants of the cascade can be used to provide control power in simultaneous hydropeaking, as opposed to only the first one in non-simultaneous hydropeaking. The required tolerance of water level deviations is almost the same in both cases; it only differs by a few centimetres in the middle barrages. This means that for the investigated cascade of the upper Danube, the tolerance of almost identical deviations from the target water levels can provide a higher range of control power in simultaneous than in non-simultaneous hydropeaking, including the financial benefits and better exploitation of existing opportunities.

The results of these studies were presented and discussed with the practice partner LEW. A review is still in progress on the extent to which the concepts presented for providing control range can be implemented in the operation of the run-of-river hydropower plants.

3.2.6.4 Training Simulator

The training simulator reflects the river section of the Upper Danube Power Plants (ODK) described in Section 3.2.1 with the existing reservoirs as a simulation model for a model-based predictive control. The training simulator aims to realistically map these different congestion positions on an operating platform to achieve optimal solutions for the sometimes competing tasks. For the simulations, all parameters relevant to the plant operator are shown in abstract form. The control and regulation of the stowage facilities are carried out via programmable logic controllers (PLC). For the training simulator, these PLCs are used as part of the hardware-in-the-loop (HiL) simulation. The user programme is processed like in a real controller. The route model of the river chain has been further developed as a hydrodynamic-numerical (HN) model in MATLAB/Simulink.

Extensive real inflow profiles of the accumulation chain are available to the operator for free selection. In addition, various static synthetic Inflow profiles can be activated for a precise analysis. Due to the large time constants in the system, the time can be compressed, stretched and paused during the simulation for diagnostic and demonstration purposes. Through manual intervention by the operator, various exceptional situations can be provoked in the simulation. The consideration of a power plant-internal incident, such as a turbine emergency shutdown, clearly shows the interactions between energy generation and water balance control on the entire storage. This leads to valuable information for not only the design or adaptation of a power plant-local controller but also an overarching control concept that encompasses barrages.

Figure 3-22 shows the schematic structure of the training simulator. Water flows from left to right from one reservoir to the next. In the uppermost power plant, water flows in as a storage chain inflow. Lateral tributaries increase the discharge, here 159 m^3/s inflow to 194 m^3/s outflow. The headwater level is given in metres above sea level (m above sea level). The local controllers regulate the upper water level and communicate with each other to increase the control quality of the water balance control. Level fluctuations are indicated in centimetres of deviation from normal congestion. The coordinator links the local controllers of the individual river sections with the HN model of the University of Kassel to create a simulation model of the river chain. If necessary, the coordinator can be connected to other systems via telecontrol protocols. Due to the modular structure, other stowage chains and individual stowage positions can be flexibly simulated and displayed in the training simulator.

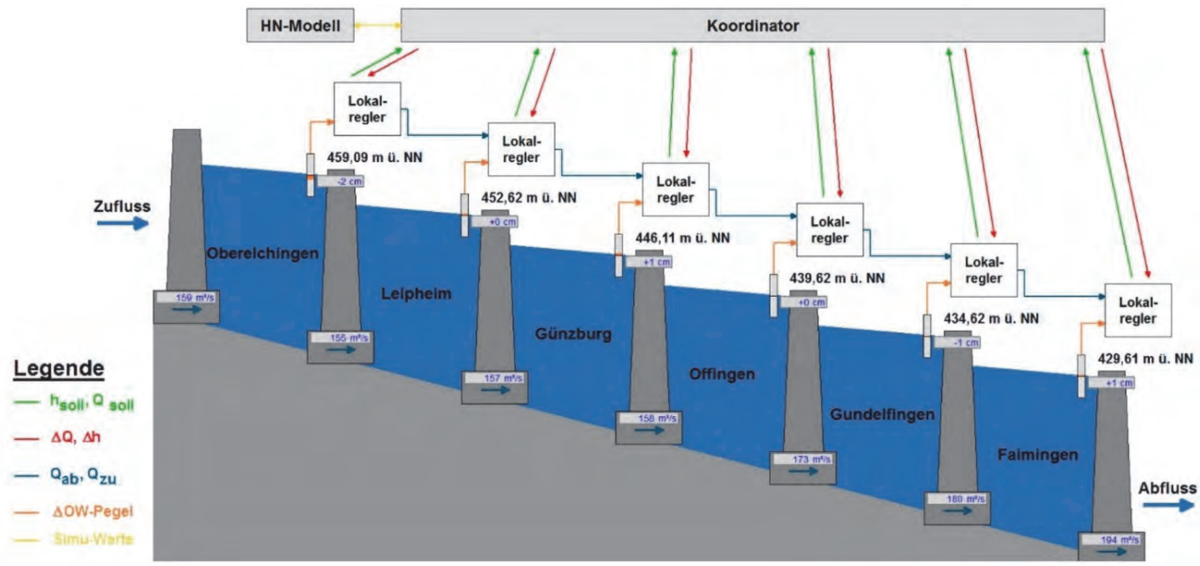

Figure 3-22: Diagrammatic overview of the training simulator with the most relevant measured values (KIMA Automatisierung GmbH, 2020)

The discharge of a river is never constant over a year. After the last power station of the ODK, Faimingen, is the Dillingen gauge station. According to the Bavarian Hydrological Service, the discharge in the Dillingen river section varies from a low water discharge (NQ) of 35.2 m³/s, an average discharge (MQ) of 162 m³/s to a high water discharge (HQ) of 1120 m³/s (Gewässerkundlicher Dienst Bayern – Messwerte Dillingen, 2020). This broad range of discharge places great demands on the design of controllers, which must always work reliably in these non-linear systems. In the training simulator, the user can select a discharge scenario from several predefined real and synthetic inflow profiles. Here, they can freely decide which discharge spectrum they would like to simulate; see Figure 3-23. A change in the hydrographs is easily possible due to the open and text-based data sources. In addition, users can enter their own data, for example, to analyse a real occurrence in more detail using a simulation.

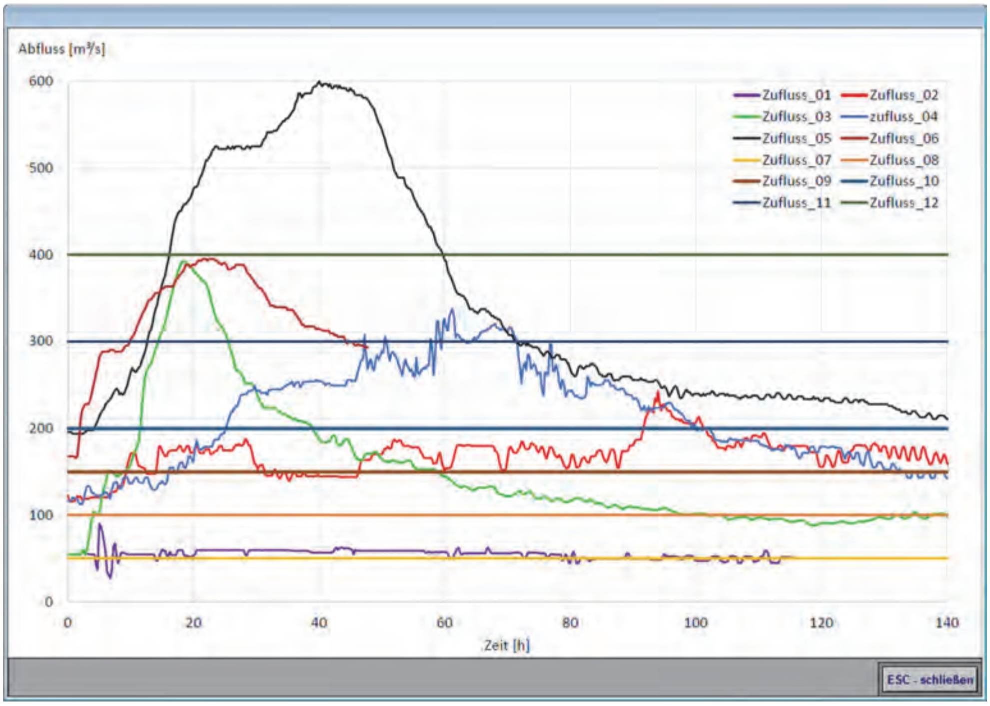

Figure 3-23: Inflow profiles (KIMA Automatisierung GmbH, 2020)

In Figure 3-24, the power plant operation is shown with the operating and display elements for each power plant. In the upper part of the figure, messages from the individual local controllers are shown. Buttons with the current status are shown in the middle and lower part. In addition to the various controller releases, malfunctions such as a communication failure and a power plant turbine emergency circuit can also be simulated.

An image of the main section is provided in Figure 3-25. In the header of the figure, various messages are displayed; there, various parts of the system can be selected and higher-level actions performed. The footer can be used to navigate to the individual pictures of the system part. In the upper section of the picture, the most relevant parameters of the training simulator are displayed. The inflow variant can be selected on the left, the state of the simulation is selected and displayed on the right – for example, the simulation time, the progress of the hydrograph and the current time factor are displayed in the image. The connection and simulation statuses are displayed to the right of this. The level and discharge curves can be scaled centrally in the x and y axes. For each power plant, the upper water level is shown graphically and as a measured value with the associated parameters. The power plant outflow is shown in the middle using the same procedure. In the lower section, the outflows from the machines and weirs are shown as measured values for each power plant, and the output of the machines is also displayed.

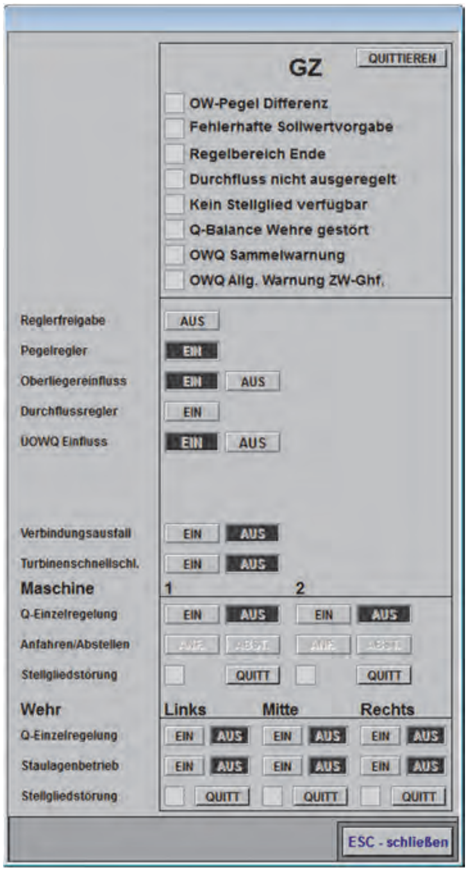

Figure 3-24: Superior power plant operation (KIMA Automatisierung GmbH, 2020)

Various messages are displayed in the header, where various parts of the system can be selected and higher-level actions carried out. The footer can be used to navigate to the individual pictures of the system part. The most relevant parameters of the training simulator are displayed in the upper part of the main screen. The inflow variant can be selected on the left, the state of the simulation is selected and displayed on the right, e.g. the simulation time, the progress of the hydrograph and the current time factor are displayed. The connection and simulation statuses are displayed to the right of this. The level and discharge curves can be scaled centrally in the x and y axes. For each power plant, the headwater levels in the upper area are shown graphically and as a measured value with the associated parameters. The power plant discharge is shown in the middle area using the same procedure. In the lower section, the outflows from the machines and weirs are shown as measured values for each power plant, and the output of the machines is also displayed.

Figure 3-25 shows the simulation of a real flood profile with the six power plants of the ODK (river course from left to right). A 34-hour hydrograph was simulated with a time factor of 20 running in 100 minutes. Initially, all power plants were in pure machine operation, i.e. the power plant runoff was discharged only via the machines. In the stored inflow hydrograph, the outflow in the chain rose continuously. By increasing the respective power plant outflows, the water balance regulators were able to regulate the upper water level in the power plant. Due to the steady increase, the automatic controller switched from pure machine operation to weir operation and from weir flap to weir segment operation. Here, as in reality, the minimum openings in the weir segments were driven. Depending on the power plant discharge, the machines, weir flaps and segments were automatically passed through different discharge areas, each considering the real specific minimum setting steps and control thresholds. The levels remain in the required tolerance ranges during the entire flood test, which, in this case, shows the correct functioning and parameterisation of the level controller.

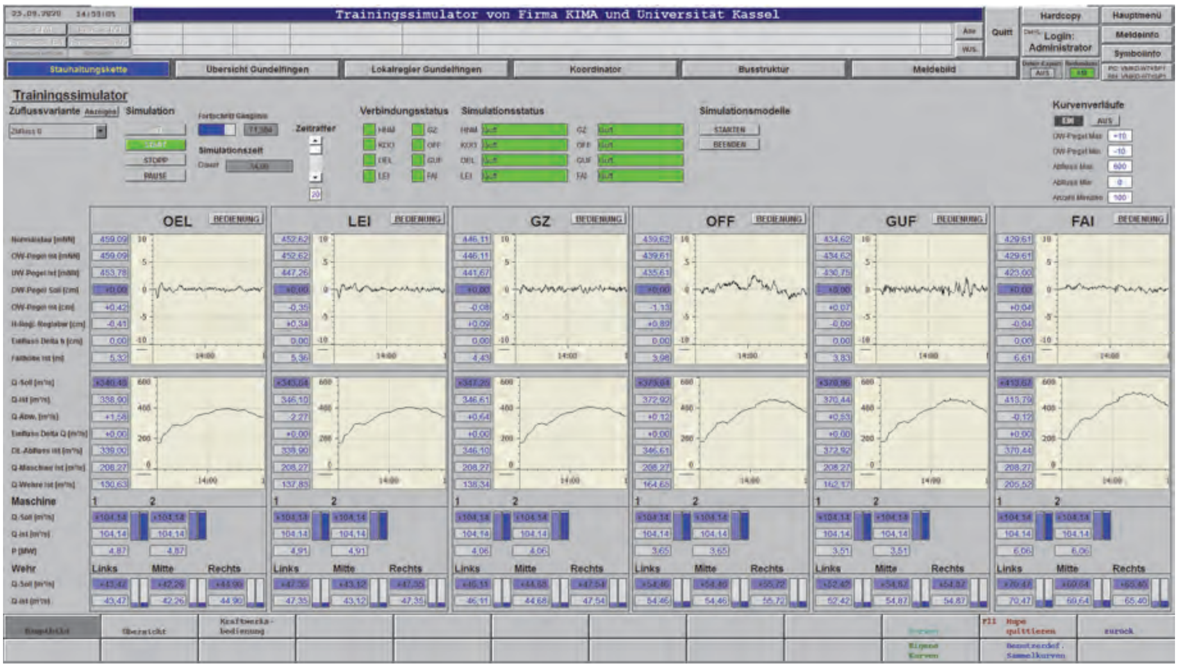

Figure 3-25: Main image of the training simulator (KIMA Automatisierung GmbH, 2020)

3.3 Concentrated Solar Power Plant – Noor-I, Draa-Valley, Morocco

Authors: Julia Terrapon-Pfaff, Peter Viebahn, Sibel Raquel Ersoy, Anna Schomberg

3.3.1 General overview of the case study

Especially in the arid areas of the Middle East and North Africa (MENA), water availability plays an important role in the expansion planning of industrial-scale solar power plants. Although power plants may account for only a very small portion of local water demand, competition for water with other sectors is expected to increase when water resources are insufficient for meeting local needs. This can lead to conflicts between different users (such as communities, farmers, tourism, businesses and utilities). Despite the increasing attention on the water–energy nexus, comprehensive studies analysing the interdependencies and potential conflicts between energy and water at the local level are absent.

To examine the linkages between water resources and energy technologies at the local level, this case study was selected because Morocco is one of the countries most affected by water scarcity and, at the same time, it is also one of the most promising countries in North Africa for the development of renewable energies and offers excellent conditions for solar and wind power plants. Nevertheless, the country's electricity system is still largely based on conventional energy sources, and the country is more than 95% dependent on energy imports. To strengthen the country's energy security and reduce the financial burden associated with energy imports, Morocco is pursuing an ambitious renewable energy expansion strategy: by 2020, around 42% of the national electricity demand should be met by renewable energies. In view of Morocco's ambitious plans, it is particularly important to identify the potential conflicts and synergies resulting from the expansion of renewable energies in relation to the water sector.

One of the most ambitious renewable energy projects is the solar complex NOOR$_o$ (Light), in Ouarzazate in the Drâa-Tafilalet region in southern Morocco (Figure 3-26). The arid environment and the high solar radiation provide ideal conditions for the solar complexes with a total capacity of around 580 MWp. The complex, which was completed in 2019, consists of four power plants, three concentrated solar power (CSP) blocks, of which two are parabolic trough systems (NOOR$_o$ I and II) and one is a solar tower (NOOR$_o$ III), and a solar photovoltaic plant (NOOR$_o$ IV). Particularly, CSP technologies can require significant amounts of water, depending on the cooling technology applied. While NOOR$_o$ II and III were already built with dry cooling technologies, which need only minimal water, NOOR$_o$ I, utilises a wet cooling system with significant water requirements. In addition, water is required for cleaning the parabolic mirrors and solar PV panels. In Ouarzazate, this water demand is covered by the only available water reservoir in the province, the El Mansour Eddahbi Reservoir. This water reservoir is also the source of water for the population and local agriculture, which is the main source of income in the province of Ouarzazate. Rather than being discharged continuously, water from the reservoir is supplied in larger quantities, known as ‘lâchers’, about seven times a year, with varying quantities of water also being supplied to the southern downstream oases (Heidecke 2009). However, currently, the water demand of the solar power plant is only marginal, with a share of about 0.8% of the reservoir water compared to the 96% of the water used for agriculture, 2.2% for the residential sector in Ouarzazate and 0.9% for the tourism sector (own calculations based on Heidecke, 2009; Busche, 2012; Wuppertal Institute and Germanwatch, 2015; Karmaoui et al., 2016). However, analyses have shown that the effects of climate change will likely negatively impact the water supply in the future (Diekkrüger, 2010, 2012). Presently, Ouarzazate is one of the driest regions in Morocco, with water availability of approximately 360 m^3 per capita per year, which is far below the internationally specified critical limit of 1,000 m^3 per capita per year.

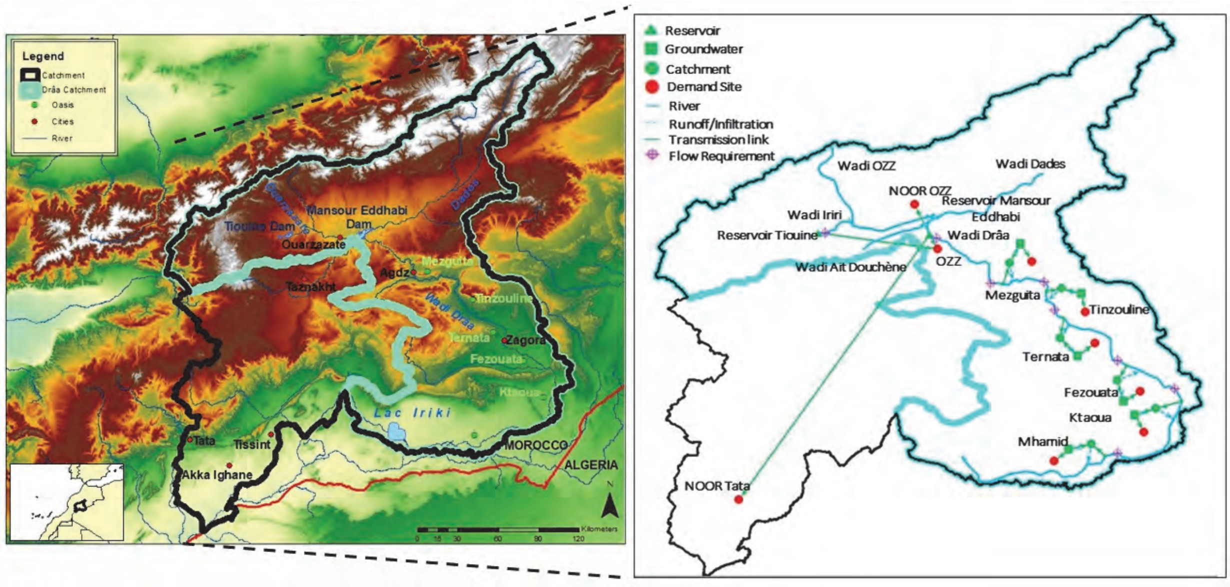

Figure 3-26: Overview of the catchment area of the Middle Drâa Valley (Ersoy et al., 2020)

Although preliminary analyses of water supply and demand exist, a systematic approach is non-existent. While existing climate models provide information on the future availability of water in the region and numerous technical developments to reduce the water demand of CSP power plants are already being researched, hardly any systematic analyses are available so far regarding the future socio-economic developments of the region and the resulting water consumption. Furthermore, the indirect impacts of the energy system on water resources have not been studied. Addressing these research gaps, the case study investigated how water availability and, as a consequence of socio-economic developments, water demand in the region will develop in the future against the background of climate change, what indirect impacts on water resources stem from the energy system and how strategies could be designed to address negative developments.

To involve local stakeholders, three workshops were conducted in the case study region in April and December 2018 as well as in October 2019. For all three workshops, representatives of local farmers, civil society groups and local and regional administration were invited. The objective of the first workshop was to develop socio-economic water demand scenarios for the Middle Drâa Valley together with the local stakeholders. The second workshop aimed to discuss water conservation measures to avoid critical water demand developments and evaluate the measures against selected criteria. The third workshop discussed governance strategies for implementing the selected water-saving measures. Figure 3-27 gives an overview of the applied methods and the stakeholders' participation in the different steps.

Figure 3-27: Overview of the research approach and stakeholder participation

3.3.2 Local water demand scenarios

To identify the key factors that influence future water demand and supply in the Middle Drâa Valley, the complex interlinkages between the surface and groundwater systems and the energy, agricultural, economic and residential sectors were mapped (Figure 3-28).

Given the complex interrelationships between the agricultural sector and water supply and demand shown in the system map, the agricultural sector is one of the key links influencing future water demand. Further aspects that are not explicitly shown in the system map but can influence the different elements of the system and thus the future water supply and demand structures are changes in the political framework conditions and potential infrastructure developments such as the construction of access roads or further dams.

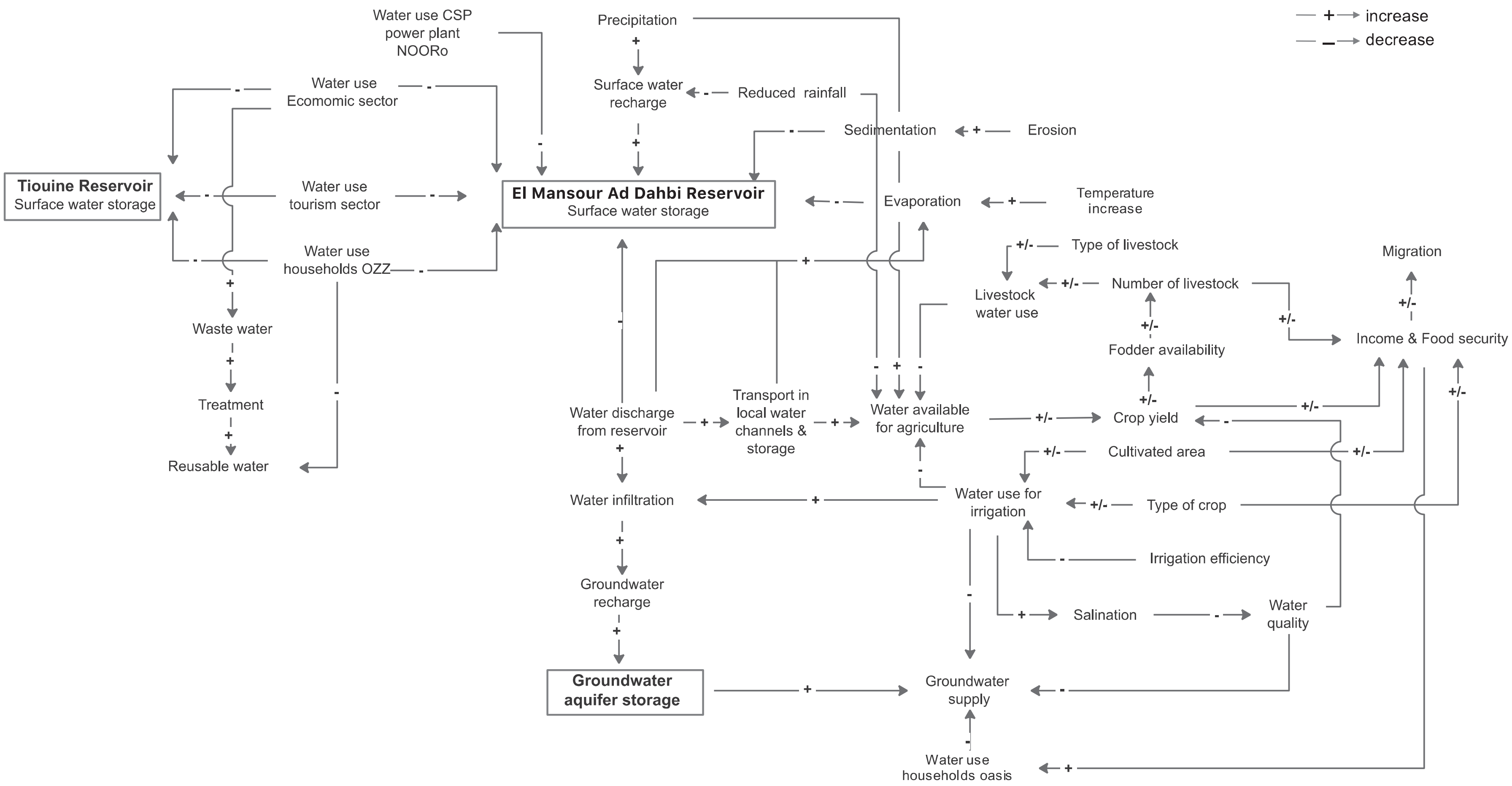

Figure 3-28: System map of water supply and demand of the Middle Drâa Valley (Terrapon-Pfaff et al., 2021)

The most critical factors influencing future water demand, derived from the system map and prioritised with the local stakeholders, include the cultivated area, choice of crop types, irrigation with groundwater, water quality, population development and tourism sector development. By linking the potential development trajectories of these factors, three scenario narratives were drafted during the first workshop by local stakeholders: one business-as-usual scenario (S1: BAU) and two more extreme but possible scenarios describing, on the one hand, an economic development scenario that is associated with the overexploitation of water resources (S2: Economic growth first) and, on the other hand, development in the direction of sustainability (S3: Growing sustainability). The drafted scenario storylines were further developed into three consistent narratives underpinned by quantitative details and data points for quantifying the future water demand and water supply implications. The water demand of these socio-economic scenarios in combination with the water demand of the solar power plant $NOOR_o$ was modelled using the WEAP software (Figure 3-29).

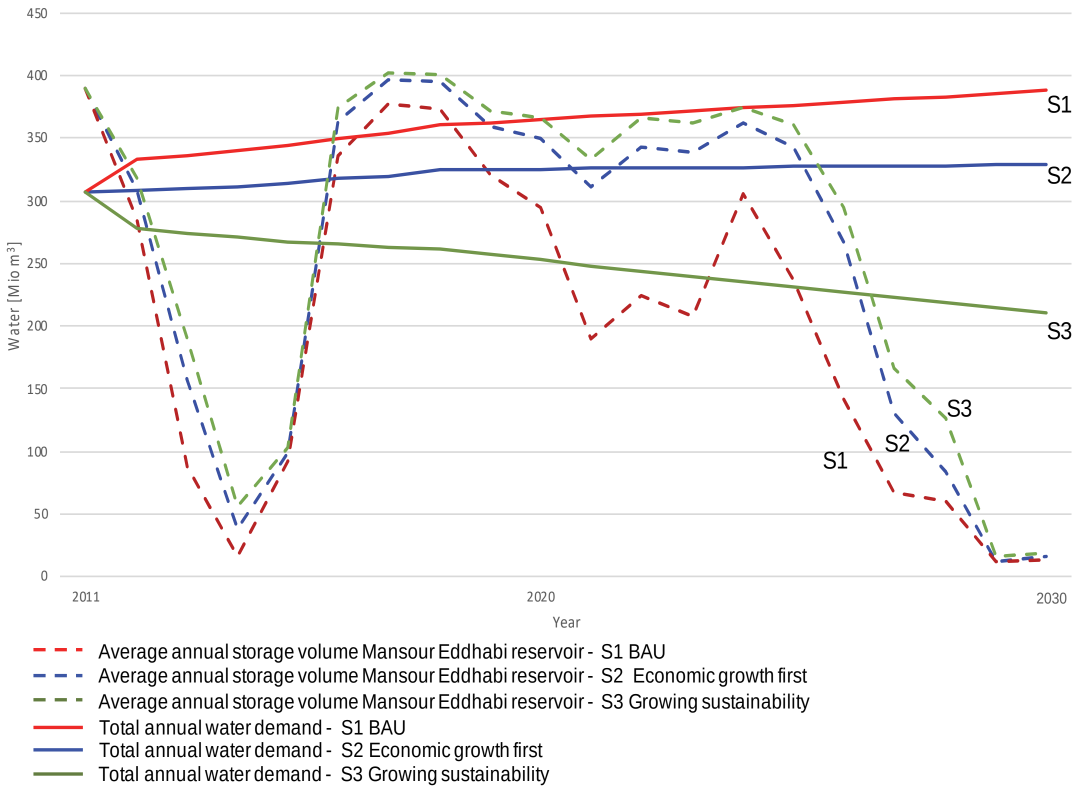

Figure 3-29: Modelling of water demand scenarios for the Middle Drâa Valley (Terrapon-Pfaff et al., 2021)

In terms of water supply, the simulation shows a general negative trend due to changes in precipitation patterns, discharge reduction, and sedimentation levels in the Mansour Eddahbi reservoir. In terms of water demand, Figure 3-29 shows a steady increase up to 2030 for the scenarios S1 'BAU' and S2 'Economic growth first'. In contrast, S3, 'Growing sustainability', indicates a decrease in water demand. In considering the water demand in the scenarios in relation to the development of water availability, it is clear that the water demand is not being met in drought years. However, in the case of S3, water demand can be met in most of the modelled years. The results show that even a transition towards sustainability, as illustrated in S3, cannot prevent water shortages in drought years, but it still offers the possibility of meeting the socio-economic water needs and NOORo power plant demand in most years. Although these scenarios and their quantification are based on several assumptions and are, therefore, subject to a range of uncertainties, the overall direction of the water demand developments is clear. Despite the apparent long-term inevitability of water scarcity in the region, measures should be taken to counteract the critical scenario developments, at least partially.

The developed scenarios illustrate that the development of water supply and demand turns out to be the more critical component in the analysed water–energy nexus context. Water becomes the limiting factor for the other sectors. In contrast, presently, water use by the $NOOR_o$ solar power plant is not critical. However, it is shown that the power plant itself may be affected by water scarcity in the future.

3.3.3 Direct impacts of the energy system on water resources

The total WSF_{quan} of the CSP in Morocco is 0.22 m^3 kWh^{-1}, with most of it associated with the operation phase (Table 3). The contributions from the operation phase are 100% direct and are associated with water requirements for cooling purposes and solar panel cleaning (details of the calculation see Appendix A). This also appears as an on-site hotspot of the WSF of the CSP (black circle around the case study location in Figure 3-30). The total WSF_{qual} is approximately 1.3 m^3 kWh^{-1} higher, with most of it being attributable to the construction phase (Table 3-3). The contributions are 100% remote and will be described further in the next section.

3.3.4 Indirect impacts of the energy system on water resources

Apart from the WSF_{quan} of the operation phase, all other contributions to the WSF come from the upstream supply chain (Table 3-3) and are therefore associated with indirect impacts. The WSF_{quan} of the construction phase is predominantly related to upstream processes that provide energy carriers, mainly hard coal and lignite, and electricity, mainly from hard coal. This indicates a large dependence of the CSP supply chain on fossil energy. At the same time, water consumption is high here. Additionally, ammonia production is represented here. As the chemical industry's demand for ammonia is generally high, ammonia production is therefore often represented in upstream supply chains. Therefore, this is not a special feature of the case study.

As for the other case studies, the WSF_{quan} of the construction phase is small compared to the operation phase. However, although the WSF_{qual} of the construction phase is high, it can be neglected for the operation phase. Treatment of hard coal ash in Switzerland and Spain, natural gas production in the US and treatment of lignite ash in Greece and Germany are responsible for 53% of the contribution to WSF_{qual}. Keeping in mind those processes without a specific location (the so-called 'global' or 'rest-of-world' ones that have been excluded from the hotspot analyses), the share from such processes that have a connection to coal combustion and natural gas production would increase to 81%. This also confirms the supply chain's dependence on fossil energy and highlights the associated high-water consumption. To improve the hotspot analysis, a better regionalisation of this upstream chain is desirable. Such high impacts associated with processes from the upstream supply that are only indirectly linked to the case studies and can hardly be touched can only be decreased by reducing the demand for resources in construction and operation and using raw materials from recycling or reuse.

Table 3-3: Cumulative LCIA indicator results for case study 3 – concentrated solar power in Morocco. For further explanations, see the caption of Table 3-1.

	Construction			Operation			Total
	total	direct [%]	indirect [%]	total	direct [%]	indirect [%]	
WSF_{quan}	4.52E-03	0	100	2.16E-01	100	0	2.20E-01
WSF_{qual}	1.25E+00	0	100	4.31E-02	0	100	1.30E+00
CED_{fo}	2.48E-01	0	100	1.35E-01	0	100	3.83E-01
CED_{re}	1.27E-02	0	100	4.00E+00	100	0	4.01E+00
EDP	1.10E-02	0	100	1.02E-04	0	100	1.11E-02
GWP100	9.98E-02	0	100	2.90E-02	0	100	1.29E-01
RMI	1.41E-01	0	100	1.24E-02	0	100	1.53E-01
TMR	1.82E-01	0	100	1.34E-02	0	100	1.95E-01
ECO	2.39E-03	0	100	5.22E-04	0	100	2.92E-03
HuHe	4.53E-03	0	100	9.31E-04	0	100	5.46E-03

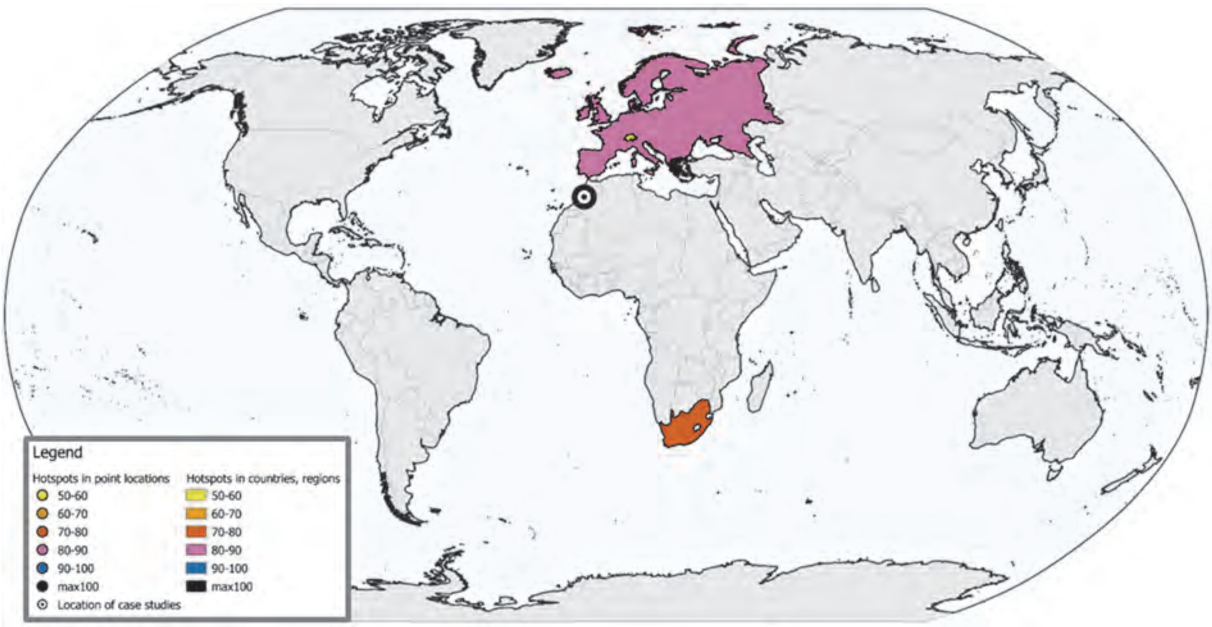

Figure 3-30: Hotspot analysis of the indicators WSF_{quan} and WSF_{qual} for case study 3 – concentrated solar power in Morocco. Further explanations, see the caption of Figure 3-2.

The WSF hotspot analysis identifies the direct water use as hotspot for the WSF_{quan} (Figure 3-30, black circle around case study location) and Switzerland, Greece, Europe and South

Africa as hotspots of the WSF_{qual} (Figure 3-30). The latter is associated with the mining of platinum group metals that are needed in the supply chain of the construction phase, while the others are related to the treatment processes described above.

3.3.5 Direct and indirect impacts of the energy system on the environment

In 2012, a Specific Environmental and Social Impact Assessment (SESIA) was implemented by 5 Capitals Environmental & Management Consulting (5 Capitals, 2012a) before the construction of Noor I. This assessment was based on various technical and scientific investigations offering information on different aspects that need to be dealt with in the ESA for this case study. Decisive information has either been considered in the LCIA indicators or is complemented as follows.

In the non-technical summary (5 Capitals 2012b) 5 Capitals pointed out that the biodiversity of the occupied land was low and 'would not be significantly impacted by the development of the proposed project.' Furthermore, no endangered species were encountered.

Regarding the impact on the landscape, the only anthropogenic elements on-site were 'a small camp for road construction and the tarmac road that is being built to connect the village of Tasselmant with the N10 and for site access'. Near the road, there were two widely visible telecommunication antennas with a negative impact on the natural character of the landscape. In contrast, the site of Noor I is visible only from a short distance of approximately 5 km along the N10 road and cannot be seen from any village or town due to the landscape's topography. As these populated areas are the most sensitive areas and the natural character along the road is already disturbed by the mentioned telecommunication antennas, the overall impact of Noor I on the landscape is neutral and negligible.

Looking at the ESA indicators, only CED_{re} reveals direct contributions. This corresponds to the result for the hydropower plants on the Danube (Section 3.2.5). Here, too, the energy input is described, but this time by the sun and not by an environmental impact. For the construction phase, the cumulative results of CED_{fo}, CED_{re}, EDP, GWP100, RMI and TMR are higher than for the coal power plant, while the results of GWP100, RMI and TMR are comparable to those of the hydropower plants. The contributions to CED_{fo} are mainly from fossile energy production around the world and to CED_{re} from forestry and hydropower globally. EDP is also associated with forestry and GWP100 with material supply from mining and the chemical industry. Especially in the latter case, however, the upstream chain is hardly regionalised, which weakens the informative value of the hotspot analysis. The contributions to RMI and TMR are predominantly from gravel and sand, hard coal and iron ore mining as well as potassium chloride production. The supply chains of hard coal and iron ore have been regionalized in the course of this project and the impacts can be assigned to the countries Australia, Brazil and China. For the other raw materials, no specific location can be identified. Regionalization of supply chains assigned to raw materials is an ongoing task of the LCA community. The indicator results for ECO and HuHe are smaller and the contributions from the construction phase are related to a variety of processes belonging to the chemical industry, material supply and fossil energy production in general. Except for CED_{fo}, the indicator results of the operation phase are throughout smaller. CED_{fo}, GWP100, RMI and TMR are to a large extent associated with natural gas production and similar processes in Russia and China, but mostly without knowing the specific location. These processes are also the largest contributors to the indicators ECO and HuHe in the operation phase, although their overall results are rather small.

The ESA hotspot analysis shows a multitude of midpoint hotspots (Figure 3-31a), also in comparison with the other case studies. Hotspots from natural gas production in the USA and Russia, forestry in Germany, solar energy from South Africa, petroleum production in the Middle East and hard coal mining in Chinese mines are linked to the construction phase of the CSP. The operation phase also holds shares on the hotspots from natural gas production in the USA and Russia and is responsible for the on-site hotspot in Morocco due to solar energy demand. This is not a hotspot of environmental impacts as pointed out at the beginning of this section. The on-site hotspots in Figure 3-31a (black circle around case study location) also comprises shares from the indicator EDP because the CSP occupies large areas of land. This is also the reason behind the on-site hotspot in Figure 3-31b from the indicator ECO, as both indicators assess land occupation (details see Section 2.2). However, both indicators can only assess the amount of occupied land here and do not include quality aspects. As the occupied land type is desert the environmental impact can still be estimated as low here.

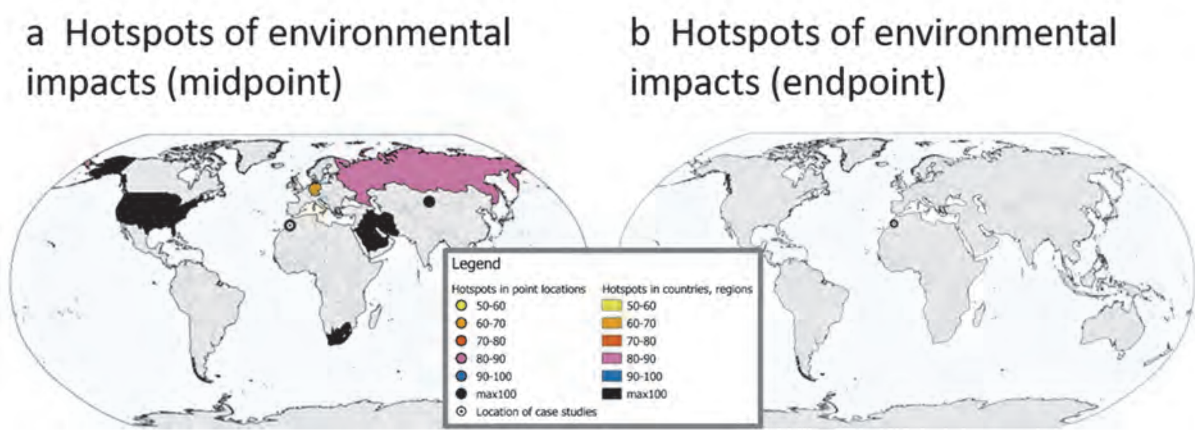

Figure 3-31: Hotspot analysis of the ESA indicators for case study 3, concentrated solar power in Morocco. Midpoint environmental impacts (CED, EDP, GWP100, RMI, TMR and WSF) and endpoint environmental impacts (ECO and HuHe) are shown separately (a and b). Further explanations, see the caption of Figure 3-2.

3.3.6 Design of instruments to address impacts

To illustrate how the most critical developments in the scenarios could be mitigated, water-saving measures, both in the energy sector and others, were evaluated against a set of sustainability criteria integrating the preferences of local stakeholders. Based on the results, governance strategies for implementing these water-saving measures were subsequently identified.

The objectives of the implementation of water-saving measures are primarily combating water scarcity and water stress and protecting surface and groundwater bodies to increase water security and enable sustainable agriculture and rural development. To achieve these objectives, as many water-saving measures as possible must be taken to at least partly mitigate the expected negative developments described by the scenarios. However, implementing these measures requires different stakeholders to become active either by, for example, changing their habits, making investments, designing regulations or building capacities. Not all water-saving measures are equally effective and feasible, and stakeholders might differ in their preferences for certain measures. Accordingly, strategic decisions on water conservation measures require – alongside the consideration of a range of technical, environmental, social, and economic issues – considering the stakeholder interests and perspectives. To this end, a participatory multi-criteria analysis approach (MCA) was applied. The approach is based on the quantitative principles of multi-criteria decision analysis in combination with participatory elements, which are integrated into the overall structure of the MCA process. To this end, the different water-saving measures (Table 3-4) were evaluated against the set of criteria (Table 3-5) by applying different weighting sets representing the attitudes of different stakeholder groups (Table 3-6).

Table 3-4: Water-saving measures (Terrapon-Pfaff et al., 2021)

Category	Measure		Short description
Water conservation measures	M1	Crop choice	Simulates a change in cropping patterns towards less water-intensive crops (e.g. arboriculture).
	M2	Irrigation practice	Describes the change in irrigation patterns from day-time to night-time irrigation, which can reduce the evaporation water loss
Water efficiency measures	M3	Irrigation efficiency	Assumes an improvement in the irrigation efficiency by applying drip irrigation
	M4	Conveyance efficiency	Covers improvements in conveyance efficiency from current open channel networks (60% efficiency) to lined channels (80% efficiency) or pipes (95% efficiency)
	M5	Precision agriculture	Covers the implementation of precision agriculture on a large scale, thereby increasing the water efficiency in the agricultural sector from the current relatively low levels
	M6	Desalination	Aims at the installation of desalination units, as the high salinity of water in the Drâa Valley is impeding agricultural production. Desalinated water can be used for irrigation to improve water productivity or drinking water quality
	M7	Wastewater treatment	Describes the reuse of treated wastewater as an alternative source of irrigation and drinking water
	M8	Rainwater harvest	Covers the harvest of rainwater for irrigation purposes and as a domestic water source
	M9	Water savings in urban households	Assumes water savings in the growing urban population, by installing water-saving appliances
	M10	Water savings in the tourism sector	Aims to reduce per capita water use by the tourism sector
Water policies	M11	Aligning national water & agriculture strategies	Aims to eliminate inconsistencies or contradictions between the 'Plan Maroc Vert' and the national water policies.
	M12	Regulatory interventions	Designates regulatory changes for either legally limiting the cultivation of water-intensive crops or providing subsidies for the cultivation of less water-intensive crops
	M13	Information campaign	This measure aims to increase the information and knowledge on water-saving technologies to allow users to make informed decisions regarding investments in technologies
	M14	Conservation-oriented water prices	This measure aims at introducing water prices to lower agricultural water use
Technical measures solar power plant	T1	Conversion NOOR 1 to Wet/Dry Hybrid	Simulates the introduction of a novel hybrid dry/wet cooling technology, which could save up to 80% of water compared to wet-only cooling, without compromising performance
	T2	Reducing cleaning water consumption NOORo I-IV	Covers the optimised cleaning schedules and implementation of devices that cut water consumption for cleaning
	T3	Maximal reduction of water consumption cooling and cleaning	Describes the maximum reduction of water consumption in the solar power plant through the application of the latest technological innovations in both cooling and cleaning as well as an additional reduction through internal reuse of water

Table 3-5: Criteria set (Terrapon-Pfaff et al., 2021)

Category		Criterion	Short description
Environment	C1	Water savings	Estimates the amount of water that could potentially be saved (including conservation and efficiency measures) by the chosen alternative if it were implemented on a large scale. The higher the potential, the more preferable the option
	C2	Water quality	Refers to the estimated impact on water quality by the chosen alternative, i.e. the ability of the option to improve water quality. The higher the potential, the more preferable is the option
	C3	Sustainability of water use	Takes the different sustainability degrees of each alternative into account. In particular, the alternatives that do not involve groundwater overexploitation but favour the use of renewable water resources are preferred
Technology	C4	Technical and operational suitability	Relates to the suitability of the technology or political instrument for implementation in the Middle Drâa Valley. The higher the suitability (feasibility and viability), the more preferable the option is
Economic	C5	Investment cost	Corresponds to the estimated initial investment for implementing an alternative. The lower the cost, the more preferable the option
	C6	Operation & maintenance costs	Captures the ongoing expenses that a measure entails, for example, for maintenance. The lower the cost, the more preferable the option
	C7	Economic benefit	Measures the ongoing beneficial effects of the measure, for example, through profits from the export of cash crops or money saved through less water consumption
Social	C8	Social acceptance	Estimates the level of social acceptance and willingness to support the chosen alternative and compatibility with traditional practices

Table 3-6: Preference weights (Terrapon-Pfaff et al., 2021)

Criteria		Average	Farmers group	Civil society group	Local administration
C1	Water savings	0.16	0.08	0.11	0.34
C2	Water quality	0.19	0.11	0.15	0.08
C3	Sustainability of water use	0.12	0.15	0.21	0.03
C4	Technical and operational suitability	0.11	0.05	0.05	0.21
C5	Investment cost	0.09	0.34	0.08	0.15
C6	Operation and maintenance costs	0.10	0.03	0.03	0.11
C7	Economic benefit	0.12	0.02	0.02	0.05
C8	Social acceptance	0.12	0.21	0.34	0.02

The results of the MCA calculations for this average weighting of preferences across stakeholders (Figure 3-32) show that the most recommendable alternatives are water conservation measure M1, which proposes a change in cropping patterns towards less water-intensive crops (e.g. arboriculture), and the efficiency measure M3, which aims at water savings by improving irrigation efficiency. Taking a closer look at the criteria scores, it can be seen that both alternatives perform particularly well in the environmental criteria categories, including contribution to water savings, water quality and the sustainability of water use. However, both alternatives do not come off well in terms of the investment costs. In this regard, the alternatives ranked third and fourth, M4 (proposing a change in irrigation patterns from daytime to night-time irrigation) and M2 (focusing on improving the conveyance efficiency by changing from currently dominating open earth channels networks to lined channels or pipes), perform better. All these measures are directed at the agricultural sector, which is not surprising, as this sector uses the majority share of the available water resources. In comparison, the technical alternatives for saving water in the solar power plant $NOOR_o$ (T1 – T3) are the least recommendable, as compared to the other alternatives, these measures do not contribute much to water savings and water quality in total and have high investment costs. Likewise, the alternatives M8 (harvesting rainwater for irrigation or domestic purposes) and M9 (water savings in urban households) received lower scores, mainly because these alternatives performed much lower in terms of water savings and water quality improvements than the other alternatives.

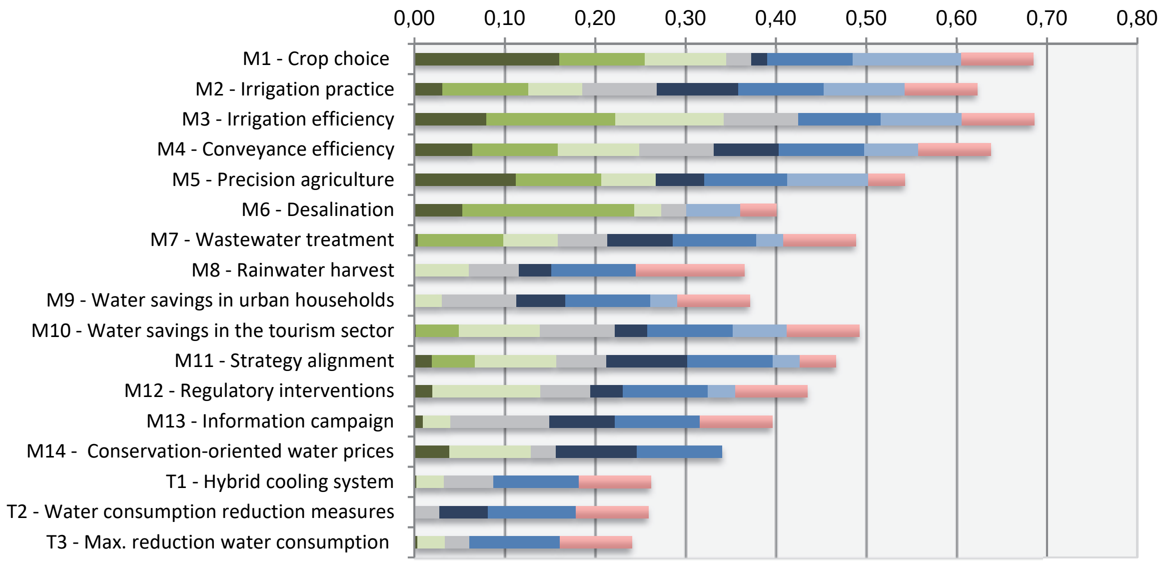

Figure 3-32: Ranking of water-saving measures (Terrapon-Pfaff et al., 2021)

In terms of the implementation of the alternatives ranked highest across preference weightings, it is to be noted that the water-saving measure that would save the highest amount of water, M1 (changing crop choices), would necessitate major changes in the agricultural practices and require a longer implementation. Measures that could be implemented more quickly but also require significant funds are improvement in irrigation efficiency (M3) and conveyance efficiency (M4). Furthermore, measures that would require changes in traditional workflows might not be easily adapted by the local communities. And although numerous barriers still exist for the preferred measures for their wide-scale implementation, it needs to be noted that the realisation of these measures can only be the starting point. To increase resilience towards the expected negative developments described by the scenarios, even the water-saving measures that were ranked lowly will need to be considered – but their implementation might be more challenging.

Table 3-7: Governance strategies discussed in the water-energy nexus context

	Strategy	Brief Description	Applied Use Case	Source/Reporting
S1	Best Practice Guides	Best practice guides summarize the possible and optimal range of activities under a given legal set.	South Africa	South African Sugarcane Institute (2019)
S2	Benchmarking	Benchmarking entails a comparative analysis of the performance based on pre-defined indicators	South Africa	South African Sugarcane Institute (2019)
S3	Intermunicipal Contracting	A flexible intermunicipal contract is a written voluntary-based co-operation agreement	Upper Franconia; Germany	Region Bayreuth (2019)
S4	Intermunicipal Cooperation	The formation of a body for intermunicipal cooperation is generally a response to capacity / resources bottlenecks.	Valle del Nalon, Spain	O'Keeffe (2011)
S5	Interdepartmental Offices	An office or council under the auspices of one ministry or department, which brings together representatives from different ministries/departments	Jordan	Breulmann (2018)
S6	Organization Culture Transformation	Interventions of organization culture change entail a management restructuring, explicit values, and new roles and practices.	Queensland, Australia	Förster (2005); Conner et al. (2016)
S7	Platform Creation with Explicit Inclusion of Traditional Methods/Leaders	A coordinating platform forms a multistakeholder board that addresses the implementation and discussion of regional issues like of e.g. a river basin plan or a lake protection plan, in this case with explicit implementation of traditional methods/leaders.	Minnesota, USA; Ontario, Canada	Coté (2016)
S8	Water Withdrawal Charges	System that charges withdrawal of water from a region's/country's water resources.	Federal States; Germany	Grawel (2012); Neumüller (2000)

Against the backdrop of these multi-layered challenges and governance strategies for implementing the measures, further research and discussions with the local stakeholders on governance strategies were conducted. This further research is in line with the call of Hoff et al. (2019) that nexus analysis should go beyond mere identification of technical solutions and provide accompanying institutional and policy-relevant recommendations.

During the third workshop in Morocco seven governance strategies (Table 3-7) were discussed and elaborated together with the local stakeholders (not counting strategy 8 (S8), which was treated separately). The strategies were pre-selected based on already existing applications and their potentially pragmatic and participatory character. In doing so, the workshop followed Hagemann and Kirschke (2017)'s call to implement and adapt already known WEF challenge strategies, to fortify and deepen systemic interdisciplinary governance research. On the other hand, top-down(-like) policies and strategies, such as those of the Green Morocco Plan, were not introduced. However, participants were given several opportunities to freely mention, discuss and attribute strategies (and top-down plans) that appealed to them.

The multi-attribute analyses revealed a stakeholder preference for S2 – Benchmarking, S7 – Tradition, Including Platform Creation and S1 – Best Practice Guides with regard to the strategies' benefit for sectors and the application of the desired measure. Furthermore, the evaluation of governance strategies for the implementation of the selected water-saving measures showed that targeted education and information of citizens should be the first step towards the introduction of water-saving measures. Furthermore, efficient assistance in the implementation of technical solutions on site was defined as a prerequisite. Likewise, it was suggested that measures from other regions of the world be combined with traditional working methods to discover new ways to counteract water scarcity.

The results of the case study can be used to support decision-making regarding energy and water development in the region.

3.4 Sugarcane Bagasse – Jalles Machado Mill, Rio dos Patos, Brazil

Authors: Jazmin Campos Zeballos, Liliana Narvaez, Zita Sebesvari, Anna Schomberg

3.4.1 General overview of the case study

Rio dos Patos basin is located in Brazil in the Goiás State, in the Alto Tocantins Hydrological Management Unit (HMU within the Cerrado Biome, which is characterised by land availability, flat topography and optimal climatological characteristics for sugarcane growth (Figure 3-33). The sugarcane production area has been continuously expanding in the Cerrados since the 1990s (Scarpare et al., 2016). According to MapBioma, around 2% of the Cerrado Biome is covered by sugarcane (MapBiomas, 2017), representing around 47% of Brazil's total sugarcane area (novaCana, 2018). It is also the biome with the highest sugarcane expansion rate in Brazil since 2006 (Arruda et al., 2017; Leal et al., 2017; Scarpare et al., 2016).

Figure 3-33 shows the location of the case study. The map was prepared based on information retrieved for the administrative areas (GADM, 2018), Cerrado Biome Area (Project MapBiomas, 2018), Hydrologic Management Unit (Agência Nacional de Águas [ANA], 2007), basin areas (Sistema Estadual de Geoinformação [SIEG], 2004), main rivers (FOREST - GIS), and the River Rio dos Patos (ANA, 2013).

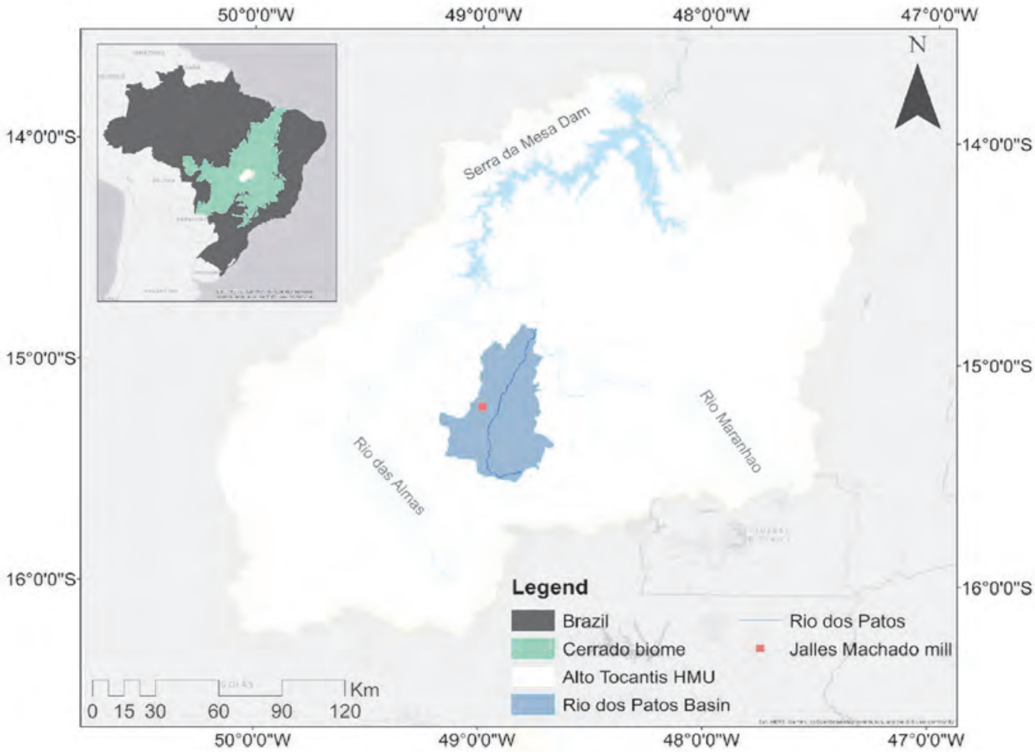

Figure 3-33: Rio dos Patos case study location

The basin is covered by irrigated and rainfed sugarcane at 22% and has the potential to expand both types, irrigated and rainfed sugarcane (see Figure 3-34).

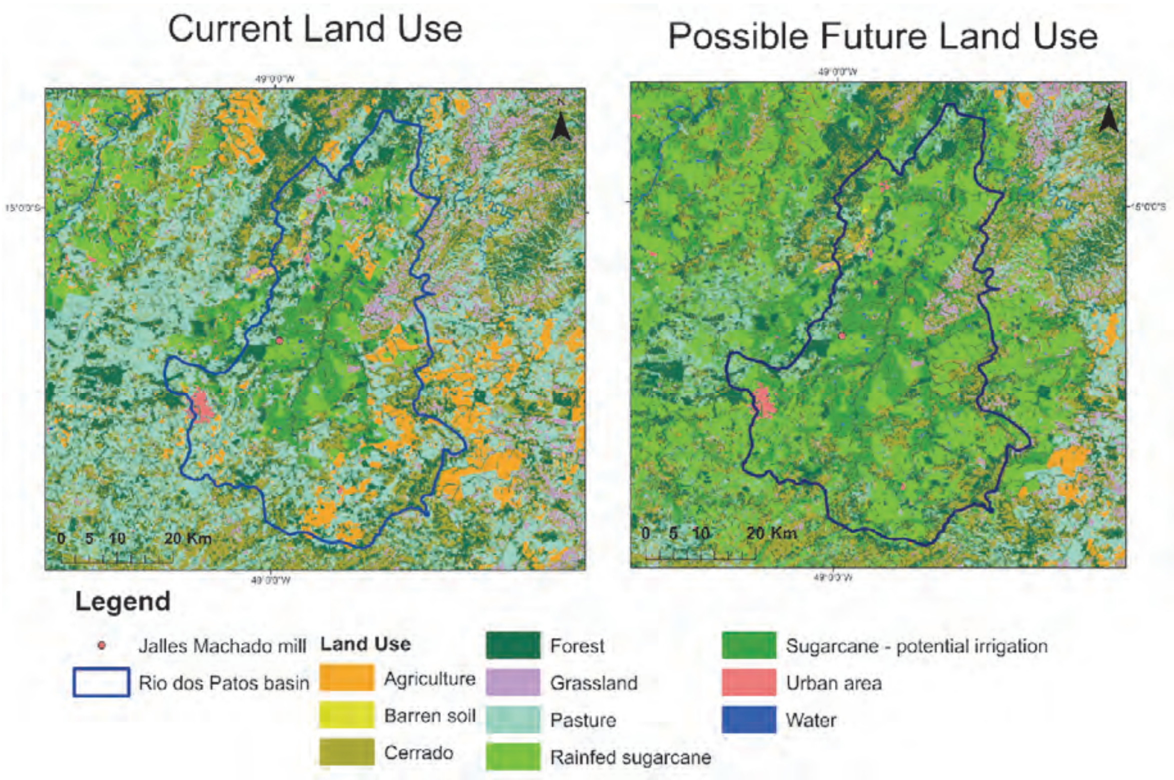

Figure 3-34: Current land use and possible scenario in Rio dos Patos if sugarcane expands to all the areas where it can be planted. Own figure based on Mundialis (2020).

The regional climate is characterised by a distinct dry and wet season (see Figure 3-35). The dry season ranges from April to October. Additionally, the temperature does not fluctuate significantly enough during the year to impact sugarcane growth. The data displayed in Figure 3-35 was retrieved from ANA (2005), Empresa Brasileira de Pesquisa Agropecuária (Embrapa) (2018) and Instituto Nacional de Meteorologia (INMET).

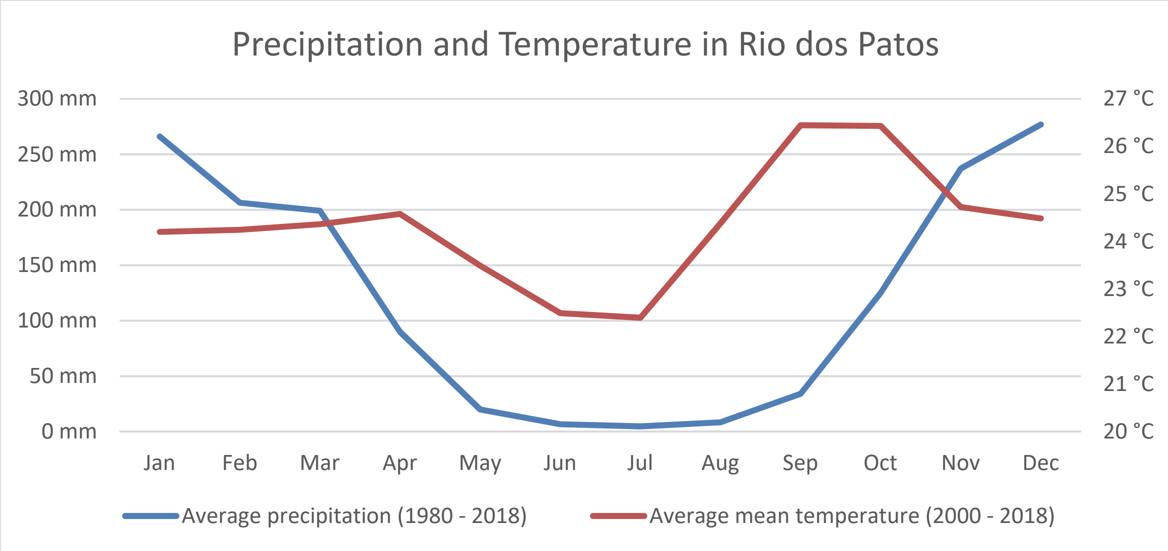

Figure 3-35: Average monthly precipitation and temperature in Rio dos Patos

3.4.2 Energy System

The energy system is composed of two subsystems: the agricultural and the industrial subsystem (see Figure 3-36). Starting the description in the agricultural system, sugarcane is harvested in the dry season between April and October, and it is when electricity is generated. Mills are designed to produce ethanol and sugar. Electricity is a by-product. Mills burn sugarcane bagasse to generate electricity to cover the electricity demand of the milling process. Depending on the efficiency of the process, surplus energy can be generated and sold to the national grid.

For the system analysis, vinasse is a relevant by-product. This potassium-rich liquid is used for irrigation and to increase sugarcane crop yield. It is combined with the wastewater of the sugarcane processing and applied to the fields. Vinasse-irrigation supports sugarcane growth based on its water and nutrient content. Additionally, to the irrigation with vinasse (ferti-irrigation), sugarcane could be irrigated to cover up to 70% of its water demand (deficit irrigation), or irrigated at the beginning of the season to assure sprout (salvage irrigation).

The agriculture subsystem can be affected by high temperatures, changing precipitation patterns, degrading soil properties, and low water availability for irrigation. The impacts manifest in reduced crop yield and crop quality. Suppose the crop yield is low or the sugarcane does not have enough water or sugar content. In that case, further industrialised products and by-products will be affected, and, for example, an insufficient amount of vinasse for the irrigation of the fields would be produced.

The industrial subsystem depends on the water availability for the sugarcane processing and the quality and quantity of sugarcane. A crucial part of the milling is the recovery of the sugarcane's water content to use in different mill-based processes. It is also important to mention that sugarcane mills can reduce their freshwater demand to 0.5 m^3/ton of processed sugarcane by recirculating water and using sugarcane water. In that sense, a modern, well-maintained mill can be a nearly closed system in terms of water use. Freshwater is mainly added as i) so-called 'make-up water' to replace water lost despite the efforts to keep water in the system and ii) to fill up the boilers, which requires higher water quality to avoid corrosion.

After sugarcane is milled, the dry material (bagasse) is burned to produce steam in boilers working at high temperature and pressure. The high-pressure steam is used to produce electricity in a turbine-generator.

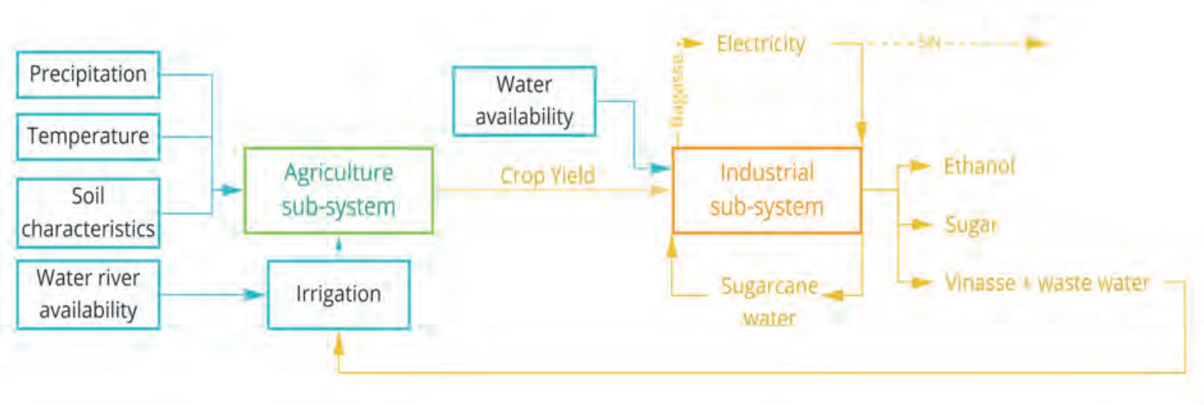

Figure 3-36: Sugarcane bagasse based electricity system (National Interconnected Electricity System (SIN in Portuguese)) (Campos Zeballos et al., in preparation)

3.4.3 Direct impacts of the energy system on water resources

The case study analysis showed that the processes related to sugarcane production and processing are changing the river regime and that it is impacting water quality. As mentioned, the region has a very distinct dry and rainy season. Farmers and the mill in the region have been building small dams to store water for irrigation and water animals during the dry season. Figure 3-37 shows the basin areas (SIEG, 2004), main rivers (FOREST - GIS), secondary rivers (SIEG, 2006), the River Rio dos Patos (ANA, 2013) and dams (Secretaria de Estado de Meio Ambiente e Desenvolvimento Sustentável (SEMAD), 2020).

The Brazilian law (Lei Federal nº 9.433, de 08/01/97) establishes that dams have to release a minimum ecological flow established by the state authority, in our case, the Goiás State Regional Government through the Resolution N° 9, Resolution N° 11, and the technical manual for granting water licences. In the case of Goiás the allocation flow is settled as 50% of the flow that has equalled or surpassed the flow record for 95%of the time (Q95), which means that the other 50% is ecological flow (ANA, 2019; Lei Nº 9.433, de 8 de Janeiro de 1997., 1997; Resolução CONAMA N° 357, 2005; Resolução N° 011, 2007; Resolução N° 09, 2005; Superintendência de Recursos Hídricos, 2012). During the visits to the case study area, four dams were visited. It could be observed that farmers build many small dams to retain water during the rainy season, and for the same reason, measurements of in- and outflow are unavailable. The outflow can be regulated to retain more water and release a minimum flow. Dams managed by the mill also present similar characteristics.

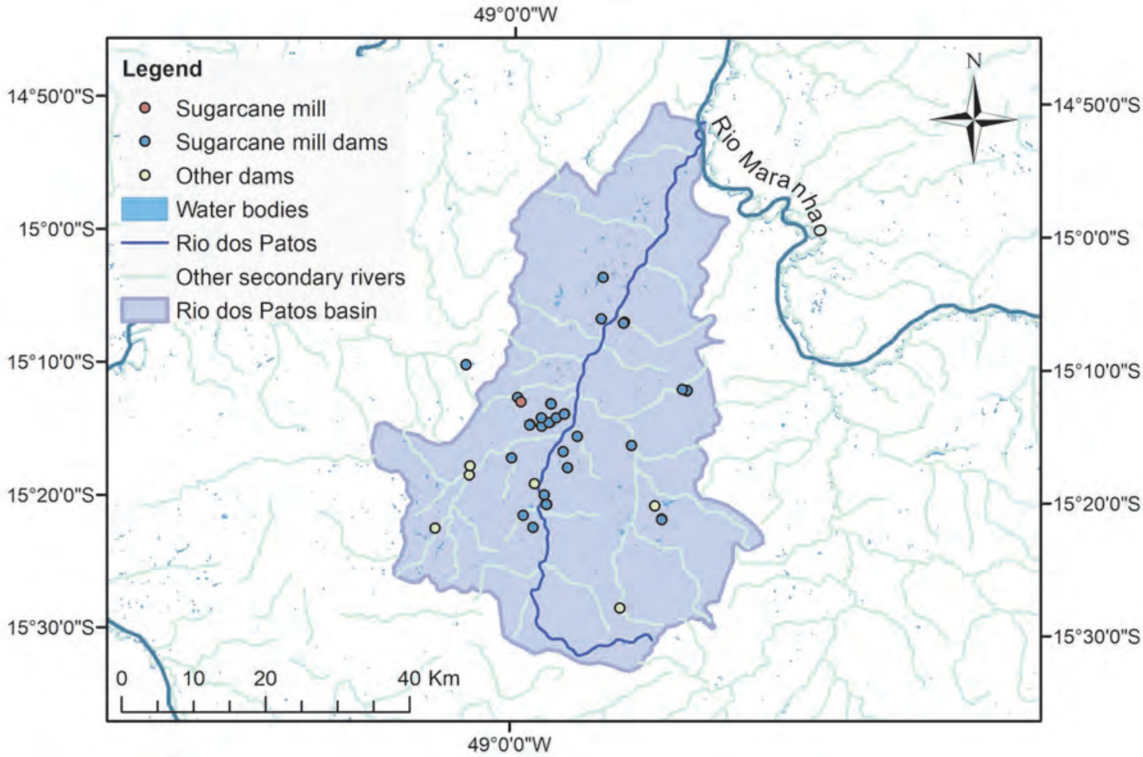

Figure 3-37: Dams in the Rio dos Patos basin

Regarding the water quality, a one-year-long water sampling was carried out by a local laboratory called Preserve. The analyses included eleven parameters: Total calcium, biochemical oxygen demand (BOD5), chemical oxygen demand (COD), total magnesium, pH, total potassium, total dissolved solids, settleable solids, sulfates, water temperature and environmental temperature. The parameters were chosen in consultation with our partner Embrapa due to their relevance to the sugarcane industry and the environmental standards. Despite the COVID-19 pandemics, the researchers managed to take monthly samples from 16 points in the basin (see Figure 3-38).

The data showed that water quality parameters were predominantly within values established by the National Environment Council (CONAMA) Resolution N°357 for freshwater class 1 (Resolução CONAMA N°357, 2005). BOD5 values were slightly higher than 3 mg/L during the August downstream of the mill and at the mill's discharge point. In February, the water sampled at the mill's discharge point showed a pH of 5.3, which is lower than the threshold established by law.

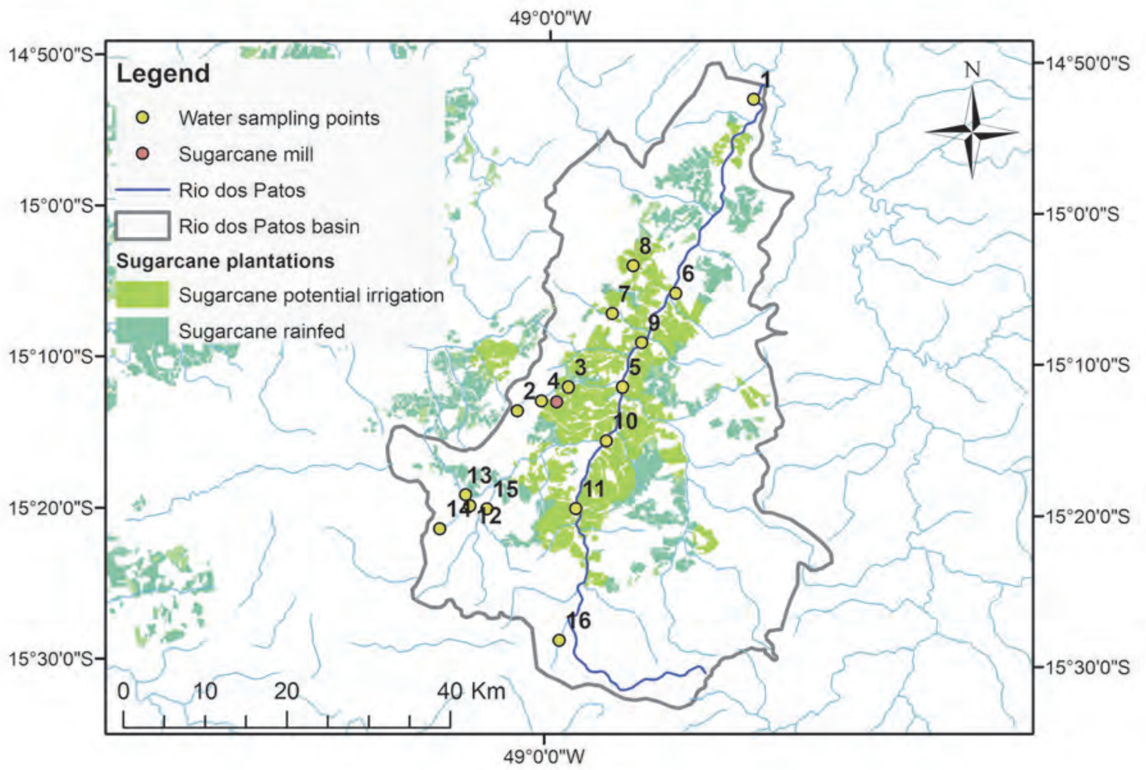

Figure 3-38: Water sampling points. Own preparation based on basin areas (SIEG, 2004), secondary rivers (SIEG, 2006) and Rio dos Patos (ANA, 2013).

For this case study, two LCA models are distinguished: in the first model, bagasse and the produced energy are considered as reference products along with sugar, ethanol and yeast (reference-product-model). In the second model, bagasse is considered as a waste product (waste-model, details see Appendix A). The description of the results in the following chapters will always deal with bagasse as a reference product first and bagasse as a waste product second.

The total WSF_{quan} of burning sugarcane bagasse that is considered a reference product is 2.2 m^3 kWh^{-1}, with almost all of it associated with the operation phase (Table 3-8). Thus, this case study has the largest WSF_{quan} of all the case studies examined. The contributions from the operation phase are 97% direct and are very predominantly associated with water requirements for irrigation (for details of the calculation, see Appendix A). This also appears as an on-site hotspot of the WSF (black circle around the case study location in Figure 3-39). The total WSF_{qual} is approximately 7.1 m^3 kWh^{-1} higher, which makes it the highest WSF_{qual} of all case studies. Most of it can be attributed to the operation phase (Table 3-8). This is a key difference from the other case studies. The contributions are 100% remote and will be described further in the next section.

The total WSF_{quan} of burning sugarcane bagasse that is considered a waste product is significantly smaller (by 0.009 m^3 kWh^{-1}) than that of the reference product model. However, similarly, almost all of it is associated with the operation phase (Table 3-9). The contribution of the operation phase is 91% direct and is associated with evaporative water loss from the boiler system where the bagasse is burnt (for details of the calculation, see Appendix A). However, due to the minimal impacts of the waste model (which does not consider the upstream supply, as waste comes burden-free), the hotspot analysis has not revealed the hotspots of WSF. The total WSF_{qual} is approximately 0.17 m^3 kWh^{-1} higher, as in all case studies. The largest part can be attributed to the operation phase (Table 3-9), as in the reference product model. The contributions are 100% remote and will be described further in the following section.

3.4.4 Indirect impacts of the energy system on water resources

For the reference product model, 3% of the WSF_{quan} of the operation phase and all other contributions to the WSF come from the upstream supply chain (Table 3-8) and are therefore associated with indirect impacts. The WSF_{quan} of the construction phase is linked to hard coal, copper and iron ore mining in Chinese, North American, Australian and Peruvian mines, where the supply chains of these commodities have been regionalised within the WANDEL project. The production of energy carriers and energy are also represented. As for the other case studies, the WSF_{quan} of the operation construction phases is large, compared to the construction phase. In contrast to the other case studies, a small share of 3% is related to the upstream supply with a multitude of processes contributing each less than 1%. It is because the cultivation of biomass is dependent on a constant supply of, for example, harvest machinery, fuel or fertiliser, the production of which, in turn, is associated with water consumption (for details of LCA models, see Appendix A). The WSF_{qual} of the operation phase is higher than that of the construction phase, unlike the other case studies, for the same reason: the constant demand for input for the cultivation of sugar cane significantly exceeds the construction effort. As for the CSP, the contributions in the operation and construction phases come predominantly from the treatment of residuals from coal combustion.

The WSF hotspot analysis identifies direct water use as a hotspot for the WSF_{quan} (Figure 3-39, black circle around case study location) and Switzerland, Spain, Greece and Europe as hotspots of the WSF_{qual} (Figure 3-39) from waste treatment processes with high aluminium emissions. This is because the regionalisation of such processes is good for Europe, but poor for the rest of the world. As it is hardly conceivable that corresponding wastes related to the case study in Brazil are actually treated only in Europe, further work is needed here to produce spatially explicit results.

For the waste-model, 9% of the WSF_{quan} of the operation phase and all other contributions to the WSF come from the upstream supply chain (see Table 3-9) and are therefore associated with indirect impacts. The WSF_{quan} of the construction phase is related to the same processes that have been described for the reference product model, but their contributions are smaller in absolute terms. As for the other case studies, the WSF_{quan} of the operation phase is greater than that of the construction phase. In contrast to the other case studies, a share of 9% is associated with hard coal mining in Chinese mines and a multitude of processes that each contribute less than 1%. The operation of the turbines requires input such as ammonia or lubricating oil (for details of the LCA models, see Appendix A) that are responsible for remote water consumption. The WSF_{qual} of the operation phase is higher than of the construction phase, unlike the other case studies, for the same reason (as with the reference product model, see above). Again, the contributions come predominantly from the treatment of residuals from coal combustion. No hotspots of the WSF were identified for the waste model.

Table 3-8: Cumulative LCIA indicator results for case study 4 – burning of sugarcane bagasse, when considered as a reference product. For further explanations, see the caption of Table 3-1.

	Construction			Operation			Total
	total	direct [%]	indirect [%]	total	direct [%]	indirect [%]	
WSF_{quan}	2.95E-05	0	100	2.20E+00	97	3	2.20E+00
WSF_{qual}	1.09E-02	0	100	7.09E+00	0	100	7.11E+00
CED_{fo}	1.73E-03	0	100	1.16E+01	0	100	1.16E+01
CED_{re}	8.69E-05	0	100	7.84E+00	98	2	7.84E+00
EDP	2.86E-05	0	100	6.09E-01	91	9	6.09E-01
GWP100	4.60E-04	0	100	3.32E+00	15	85	3.32E+00
RMI	1.30E-03	0	100	1.70E+00	0	100	1.70E+00
TMR	1.71E-03	0	100	2.17E+00	0	100	2.17E+00
ECO	1.20E-05	2	98	2.63E-01	82	18	2.63E-01
HuHe	4.37E-05	0	100	1.28E-01	27	73	1.28E-01

Table 3-9: Cumulative LCIA indicator results for case study 4 – burning of sugarcane bagasse, when considered as waste. For further explanations, see the caption of Table 3-1.

	Construction			Operation			Total
	total	direct [%]	indirect [%]	total	direct [%]	indirect [%]	
WSF_{quan}	2.89E-05	0	100	8.98E-03	91	9	9.01E-03
WSF_{qual}	1.06E-02	0	100	1.59E-01	0	100	1.70E-01
CED_{fo}	1.70E-03	0	100	4.26E-02	0	100	4.43E-02
CED_{re}	8.45E-05	0	100	1.34E-02	0	100	1.35E-02
EDP	2.77E-05	0	100	7.45E-03	0	100	7.48E-03
GWP100	4.47E-04	0	100	5.07E-02	78	22	5.11E-02
RMI	1.22E-03	0	100	4.92E-02	0	100	5.04E-02
TMR	1.62E-03	0	100	5.73E-02	0	100	5.89E-02
ECO	1.15E-05	2	98	1.46E-03	59	41	1.48E-03
HuHe	4.27E-05	0	100	n.a.			

Figure 3-39: Hotspot analysis of the indicators WSF_{quan} and WSF_{qual} for case study 4 – burning of sugarcane bagasse, when considered as reference product. Further explanations, see the caption of Figure 3-2.

3.4.5 Direct and indirect impacts of the energy system on the environment

To assess the impact of the Jalles Machado Mill on the landscape, it is unnecessary to differentiate the reference product model from the waste model. This is because many parts of the buildings and technical installations are looked at for both approaches and do have a group effect on the landscape. As Jalles Machado Mill is located next to the GO-080 road about 17 km northeast of Goianésia and the next settlement is located more than 2 km northeast of the site, it is not visible from these populated places. Therefore, the Jalles Machado Mill has an insignificant impact on the landscape.

However, in this context, it is important to highlight that the large-scale plantation of sugar cane around the mill changes the landscape severely. This is not considered as an on-site impact, but rather, regarding the LCA terms, as a remote impact along the supply chain located in the Rio dos Patos basin. Following the described ESA method, such impacts are identified and analysed using indicators, which is impossible in this case because there is no indicator capable of illustrating the impacts of visibility.

Looking at the ESA indicators of the reference product model, several indicators reveal direct contributions, especially in the operation phase, reaching from 2% to 82%. This confirms the finding of Section 3.4.4 that biomass cultivation is associated with significantly more direct environmental impacts than the other case studies. For the CED_{re}, again, only the energy content of the biomass is considered on-site; energy requirements in connection with the production of this type of biomass are reflected elsewhere. Furthermore, the absolute indicator results are the largest in this comparative study, which raises suspicions that biomass considered as a reference product is responsible for relatively high environmental impacts. Remote contributions are relevant for the indicators CED_{fo}, GWP100, RMI, TMR and HuHe. The contributions to the CED_{fo} are mainly from fossil energy production all around the world, with the largest share being petroleum production. GWP100 and HuHe are linked to the burning of diesel in building and agricultural machinery, while RMI and TMR are associated with processes that are already well known from the results of the other case studies: petroleum and gas production as well as gravel and sand quarrying, with smaller contributions from iron ore and hard coal mining. Phosphate rock beneficiation in Chinese mines accounts for only 2%, but it is important here, as its supply chain has been regionalised in the course of the WANDEL project to account for phosphate rock as an important raw material for fertiliser. It again shows that the regionalisation of upstream chains of required inputs is useful in terms of comprehensive analyses. Impacts from the construction phase can be neglected when compared to the operation phase.

The ESA hotspot analysis shows the most midpoint hotspots (Figure 3-40a) of all case studies. All the hotspots are linked to the operation phase. Contributions of the sugarcane cultivation to the indicators CED_{re}, EDP and GWP100 (Figure 3-40a) as well as ECO and HuHe (Figure 3-40b) create on-site hotspots at the location of the case study. When it comes to remote hotspots, petroleum production in Canada, Africa, Middle East and Russia are responsible for hotspots of the indicator CED_{fo}, while all the other hotspots come from different mining and refining activities as contributions to the RMI and TMR.

Looking at the ESA indicators of the waste model, the GWP100 and ECO reveal direct contributions from the operation phase that are 78% and 59% higher than the remote shares. Both are associated with the process of electricity generation itself. All other contributions are at least 98% remote.

Forestry at unspecific locations provides the greatest contributions to the CED_{re} of the construction and operation phases, which is also visible in the results of the indicator EDP. However, the greatest contribution to the EDP in the construction phase comes from the construction of the turbine at an unspecified location, which is also the greatest contribution to the ECO. Processes that contribute to the GWP100, RMI, TMR and HuHe are already well known from the evaluation of the other case studies so that no new information arises specifically for the waste model. As for the reference product model, all the indicator results are higher for the operation phase, although the bagasse is provided burden free, if considered as a waste product. As the share of electricity generation in the sugar mill infrastructure, which was considered for construction in addition to the infrastructure for combustion itself (boilers, turbines, etc.), is only estimated and may be higher in reality, it is possible that the construction phase has been underestimated. However, a clear separation of the different parts of the plant is hardly possible. In comparison to the other case studies, the burning of bagasse, when considered a waste product, achieves similar indicator results as the coal-fired power plant for the construction phase and as the CSP for the operation phase.

The ESA hotspot analysis shows on-site hotspots related to the EDP (Figure 3-41a) and ECO

(Figure 3-41b), both from the sugarcane production process. The hotspot in Canada is associated with forestry and the one in Switzerland with gravel and sand quarrying. Most likely, both result from a poor regionalisation of such processes for Latin America. As timber, gravel and sand are also available there, they are probably not truly delivered from Canada and Switzerland.

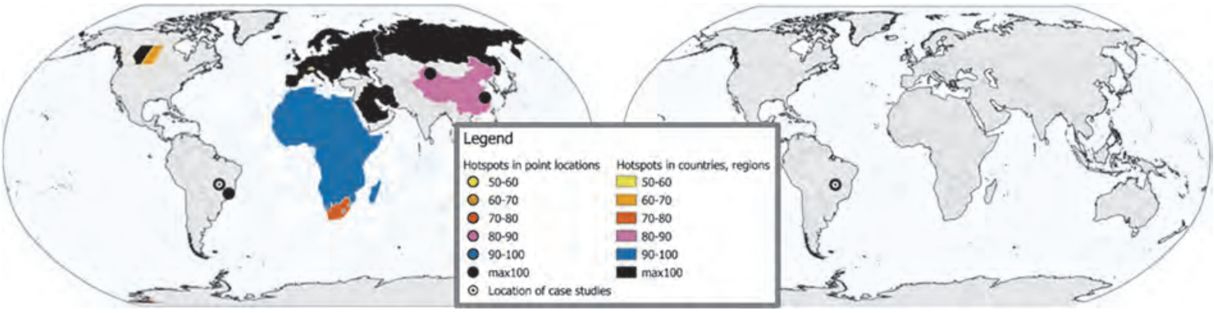

Figure 3-40: Hotspot analysis of the ESA indicators for case study 4 – burning of sugarcane bagasse, when considered as reference product. Midpoint environmental impacts (CED, EDP, GWP100, RMI, TMR and WSF) and endpoint environmental impacts (ECO and HuHe) are shown separately (a and b). Further explanations, see the caption of Figure 3-2.

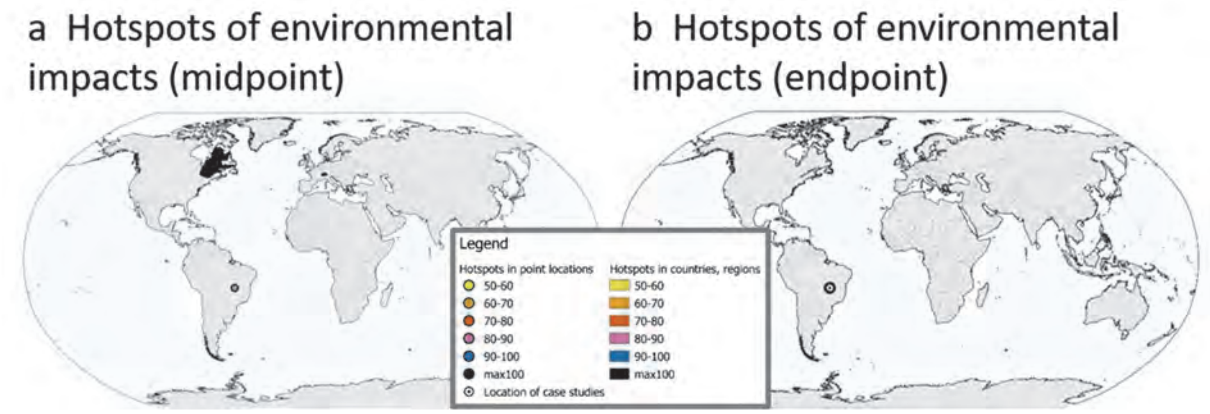

Figure 3-41: Hotspot analysis of the ESA indicators for case study 4, burning of sugarcane bagasse, when considered as a waste product. Midpoint environmental impacts (CED, EDP, GWP100, RMI, TMR and WSF) and endpoint environmental impacts (ECO and HuHe) are shown separately (a and b). Further explanations, see the caption of Figure 3-2.

3.4.6 Design of instruments to address impacts

During the project, a series of semi-structured expert interviews regarding the federal and Goiás state legal systems and water resources administrations were produced. The semi-structured methodology prescribes aim-based questions but guarantees enough degree of freedom for the interviewee to mention their own experiences and opinions that might not directly answer a question but delivers valuable insight and content (Adam, 2015). It is important to stress that the anonymity of the interviews and the diverse background of the experts (NGOs, governance, science and economy) guaranteed a vast, deep and pluralistic insight into the Brazilian and the Goiás's efficient execution of legal systems and administration, which led to the subsequent insights and recommendation of the instruments for addressing the identified impacts.

Next to the expert interviews, research on scientific and media publications and official data from Brazilian federal and state governments were utilised to survey the administrative and jurisdictional situation of governance in the state of Goiás, the Federal District and, wherever possible, the research areas of the basins. To evaluate the situation in Goiás, the other states of Brazil were used as a basis of comparison, particularly Minas Gerais, the neighbouring state. Moreover, literature produced by the OECD on Water Resources Governance in Brazil (Organisation for Economic Co-operation and Development [OECD], 2015), reports produced by several ministries of Brazil, as the Brazilian Energetic Review by the Ministry of Mines and Energy (Resenha Energética Brasileira in Portuguese), the Hydric Resources Conjuncture and the Legacy Project documents from ANA (ANA, 2017), were consulted. There are clear deficiencies in the water governance in Goiás, demonstrated by the conflicts occurring in the region, the constant changes in the local state administration of water resources, and the presence of areas not covered by the basin committees (Camporez, 2020; Félix, 2018; Magrineli, 2020) To a highly important degree, the Goiás' state governance factors are impacted by Brazil's federal law and administration. A determining factor of the country's water governance is Brazil's size. Internal differences exist among not only users but also states (Félix, 2018, 2020), where different regions and states have completely different climates, economies, populations and sizes. The Centre-West of Brazil (which includes Goiás) does not have a long tradition of undertaking development in water governance and management due to its lack of conflict over water and pressure from the agricultural sector, the most significant economic sector of the region (Magrineli, 2020). The inherent federal urge for uniformity in the legal system in applying laws is thus not realistic at present.

Nonetheless, Brazil has settled on the decentralisation of water resources management, given that the rivers can be in the jurisdiction of the state or the federal government. Based on the course of the river, the jurisdiction falls under one of these spheres: if the river flow within the state boundaries, it falls under the state jurisdiction, and if the river flows across two states or borders two states or another country, it is under federal jurisdiction. Despite being praised on many levels, such a choice for decentralisation creates challenges and has received criticism, e.g. for not taking into consideration the municipalities involved in the watercourses (de Oliveira Domingues, 2018; Lima, 2018). The Water Law in Brazil is recent, dating from 1997, and the Brazilian National Water Agency (ANA) is from 2000. Since that period, although the state laws and committees have been gradually incorporated state organs into the current framework, many states have been extremely unstable, shifting according to the governor's interest (Félix, 2018, 2020). Both the laws as well as the apparatuses, federal and state, need time to mature and become efficient and gain space among other public organs, something strongly undermined by the inconstancy that marks water governance in Brazil (Magrineli, 2020).

Moreover, another challenge in Brazil is the lack of implementation of laws. This affects another key aspect of water governance in Brazil, which is access to data from other government sources. While all public data should be freely accessible in Brazil, the ANA still faces difficulties in accessing data necessary for effective water governance (Freitas, 2018; Lima, 2018). That reflects a common difficulty of water management organs, federal or state, in dealing with other organs (Félix, 2018; Freitas, 2018). The lack of maturity in governance was conspicuous in Goiás due to the constant changes in the state management of the water resources. During this project, the secretariat had a significant staff change and even the name of the secretariat changed. In comparison to the state of Minas Gerais that has three different websites on different water governance tools, Goiás's water management secretariat is fused with the Environment and Sustainable Development secretariats. Goiás has a large area that is not inside any basin committee (among them the research area), and even areas within the scope of a basin committee have problematic conflicts because of water, such as the region around the lake of the Batalha power plant (Camporez, 2020; Félix, 2018). To a considerable extent, Goiás has deficiencies common to the rest of Brazil, such as the absence of a mature governance system, the lack of municipality involvement, and a culture that seeks more water instead of using water more efficiently.

Based on interviews and research on water management in Brazil, the following points were considered for an improvement in the use and management of this resource in Goiás:

- Greater involvement with the ANA's Progestão and Procomitê, particularly in the Procomitê, to bring more equality to the different water users of the Committees.
- Greater involvement of municipalities in state water management.
- Partnership with the MG system for water management and an evaluation of this management.
- Creation of a website dedicated exclusively to water management.
- Development of programmes to encourage more efficient use of water for irrigation that avoids waste and stimulates reuse while encompassing smaller producers.
- Creation of water governance tools in regions with no basin committees.

Particularly important structures are Committees, which theoretically are quite strong and democratic. Government participation is limited to 40%, including the three spheres of government. The region's water users have 60% of the votes of the Committee, divided among energy producers, farmers of different sizes, and civil society through NGOs. The Committees are councils that recommend the policies to be followed in the basin over which they govern, counting on a way of self-financing that guarantees greater independence. This system guarantees equality among users and prevents the 'big ones' from overtaking the 'small ones', as the groups are organised, thus leading to a consensus on the guidelines for the use of the basin and water resources. It is a promising and democratic tool but faces limitations with significant internal cleavages, where, many times, we have impoverished farmers deliberating with highly educated engineers of the robust electric sector or big farming conglomerates. This holds especially for areas in the sparsely settled area of the Centre-West (and thus Goiás).

Today the ANA has Progestão e Procomitê, programmes that seek to address this difference at the federal and state levels of water resources management and resolve the internal difference between committee participants. Projects such as Progestão and Procomitê should be maintained and strengthened, causing non-participating states and basins in Goiás to enter the projects. A change in management is not possible without the will of society and local government thus, the ANA must foster discussion and partnerships with state governments and assist in restructuring agencies and seeking ways to maintain a state water office in each state. QUALIÁGUA was a project created to disseminate surface water quality data in Brazil, standardise water quality criteria and methods and strengthen the states' water governance structure to improve the water monitoring and generate more open-source data (ANA, n.d). A project such as QUALIÁGUA can be used to disseminate data in a way that creates discomfort for states that perform worse, thus inducing in them a willingness to adapt to the established goals. To do so, the program must evolve to become more visible and efficiently implement the National Water Quality Monitoring Network.

3.5 Lessons Learned from the Case Studies

Authors: Jazmin Campos Zeballos, Swantje Dettmann, Sarah Dickel, Sibel Raquel Ersoy, Liliana Narvaez, Zita Sebesvari, Anna Schomberg, Julia Terrapon-Pfaff, Stephan Theobald, Peter Viebahn, Tobias Vogtmann,

3.5.1 Case study 1 – Weser drainage basin, Germany

Reservoirs create a balance between time-varying water supply and water demand by temporarily storing the inflowing water. From the respective catchment area, water is usually stored during winter months, characterized by high levels of precipitation, and, according to management objectives, is being released during the drier summer months. For the Eder reservoir, storage is mainly used to maintain minimum flow in certain river sections located downstream and for withdrawal of water in order to keep the Oberweser navigable. The simulation and optimization model that was developed in the process of the project, provides a versatile tool that meets these operational aims. It ensures analysis and optimization of water use on the Oberweser through simulation and optimization runs for various management cases. This allows the identification of measures for an adaptive management of the available water resources. In the case of optimizations with short-term requirements, such as the availability of a certain discharge for navigation support, the tool ensures the supply of the appropriate amount of water from both reservoirs at the time required, which in turn enables the required discharge to be achieved with a minimum of water resources used. The use of the water supply is thus optimized with all boundary conditions considered.

For the scenario with raised low flow, it turned out that a long-term water supply is hardly practicable in the event of persistent droughts. If the temporarily stored water mass is exhausted, no further raise of low or maintained shipping levels can be achieved.

With regards to climate change, distinctive periods of low water conditions can be expected, due to a decline in mean precipitation in summer, especially on the Werra and Oberweser. This intensifies the problem of temporal distribution of the water supply over the course of the year, further emphasizing the importance of storage use. The Eder reservoir is already heavily used throughout the year, it reaches its full storage in April and is often depleted to 10% fill level in August or September. Modifying the management objectives, such as the minimum discharge at a certain level in the system, can help to reduce the discharge and save water for the needs of short-term management objectives.

3.5.2 Case study 2 – Cascade of six hydropower plants on River Danube, Germany

Hydropower is a versatile and widely used, renewable power generation technology. It can be used to cover base load needs as well as to generate peak or control reserve energy. Since its life cycle assessment results are superior to those of all other forms of electricity generation in terms of greenhouse gas emissions and EROI, its effective use is of particular importance.

The simulations show that an increase in the target water level of the upper Danube reservoirs by $\Delta z = 15$ cm could increase the electricity production by 1 - 1.8% (depending on the discharge). However, this result is to be regarded as hardly feasible, as it would require a modification of legal concessions of water abstractions. A potential need for physical modifications of the plant was not investigated further.

Smoothing the discharge (by allowing a tolerance range for the water level) also smoothes the electricity generation of the cascade, but does not affect its total amount. It is nonetheless very beneficial for the downstream plants, as it considerably reduces the wear caused by continuous movements of the regulators. According to these findings, it is highly recommended to implement an overarching control system in cascades of hydropower plants for continuous smoothing of discharge fluctuations.

The investigations on specific operation strategies that target a temporary increase or decrease of electricity production showed that a cascade of hydropower plants is well suited to provide control reserve. Two different strategies were investigated. In simultaneous hydropeaking the discharges are manually altered at all of the hydropower plants, whereas in non-simultaneous hydropeaking only the discharges of the first and the last hydropower plant are altered. While the water level tolerances required for the two strategies hardly differ, the marketable control reserve is significantly higher in simultaneous hydropeaking since the activation time can be specified at all reservoirs, a prerequisite for control reserve, whereas in non-simultaneous hydropeaking this is only true for the first reservoir.

3.5.3 Case study 3 – concentrated solar power plant – Noor-I, Draa-Valley, Morocco

With regards to the methodological challenges of operationalizing the WEF nexus at local level, the participatory approach and the application of both quantitative and qualitative methods allowed a comprehensive analysis, considering both the resource and human dimensions of the nexus as called for by Albrecht et al. (2018).

The developed scenarios illustrate that the development of water supply and demand turns out to be the more critical component in the analyzed water-energy nexus setting. Water becomes the limiting factor for all other sectors. In contrast, water use for energy is not at critical levels to date. However, modeling of water availability and demand in the region shows that the power plant itself may be impacted by water scarcity in the future.

The scenarios developed together with local stakeholders show that even with major changes towards sustainable water use in the Middle Drâa Valley, the energy and agriculture sector and hence the local livelihoods will most likely be negatively impacted by the diminishing water supply.

During the discussion with local stakeholders, it became clear that for the implementation of water saving measures, targeted education and information of citizens, assistance in the implementation of technical solutions and the inclusion of traditional working methods were seen as prerequisites. The results of the case study can be used to support decision-making for energy and water development in the region.

3.5.4 Case study 4 – sugarcane bagasse – Jalles Machado Mill, Rio dos Patos, Brazil

The drought risk assessment results of Rio dos Patos basin showed the importance of the protection of key areas (for example riparian areas) to reduce drought risk and drought impacts as well as the need for a platform to monitor the protected areas in order reduce the overall risk. Protected areas reduce the vulnerability of the region to water related hazards, while the monitoring in-creases the awareness of farmers for the importance of these areas.

Access to weather forecast and information about soil moisture was found important to reduce the drought risk of sugarcane production; however, an early warning is still missing in the sector and it contributes to the vulnerability of the system.

Farmers, mill managers, and researchers are aware of the impacts of climate change and drought events. Farmers are willing to provide monetary contribution or land to build small dams and water storage for the dry season and they believe that these are a crucial adaptation mechanism of the sugarcane system to climate change and drought events.

Brazil recognized the need to adapt the energy sector to climate change in its National Adaptation Plan. However, there is still a need to bridge science with policy. Research has been key to reduce irrigation requirements in sugarcane plantations and to improve the mills water use and electricity generation. During the visit to different institutions, it was clear that the research lines and actions were mostly planned without agreement with other institutions and some were not aware of the research undergoing in the sector. This is mainly driven by the constant change of regional government authorities. Regular meetings between researches, farmes and mill managers with governmental authorities will help to create a better path to adapt the energy matrix to climate change and to improve the electricity generation based on sugarcane.

3.5.5 General findings from the analyses of environmental impacts and comparison of the four case studies

Some general statements can be derived from the analysis of environmental impacts for the four case studies:

1. Regionalization of global supply chains of the chemical industry, gravel and sand quarrying, natural gas production and forestry is absolutely necessary to better assign environmental impacts to their most likely location. Especially in the case of water, this is crucial to identify hotspots.
2. From the distribution of on-site and remote impacts, some general findings can be derived: apart from a few exceptions, the impacts of the construction phase are 100% remote (see also 4.), while the operation phases of coal and bagasse combustion also have on-site impacts. Furthermore, the quantitative Water Scarcity Footprint (WSF) of the operation phase is, except for the coal-fired power plant, always greater than 90% on-site, indicating that in such cases measures for optimization can be made on-site. The qualitative WSF never has on-site shares, as no on-site aluminium emissions are associated with the examined case studies.
3. High impacts associated with processes from the upstream supply that are only indirectly linked to the case studies can hardly be evaluated at the analytical level, and certainly not through measures that start from the case studies (e.g., high water demand for fossil energy carriers and energy production in the supply chain of CSP). This is more a problem of global supply chains. Reduction of resource demand for construction and operation of the case studies or supply from reuse and recycling is currently the only possibility to reduce such impacts.

Regarding water use in particular, the analyses of the WSF gained the following insights:

1. 1. Bagasse, if considered as a reference product, has the highest quantitative WSF (regarding the importance of the reference-product-model see also below), followed by the CSP, hydropower, the coal-fired power plant and bagasse which was considered as a waste product. Hence, the water requirement for renewable electricity generation may well exceed that for fossil electricity generation. However, the locations of the case studies influence this result, due to the regional assessment of the water demand (e.g., Morocco), as well as data uncertainties (e. g. hydropower, details see also Appendix A). For the global energy transition this implies that spatially explicit studies should always be carried out for energy generation plants and options to reduce water demand should always be the subject of the planning phase.
2. This result also shows that water footprint alone cannot answer the question of overall sustainability. It is to be expected that coal-fired power is associated with significantly higher environmental impacts than concentrated solar power or hydropower, if one disregards the water requirement. Other environmental impacts should thus always be considered. This highlights the importance of the ESA developed in the WANDEL project.

3. The qualitative WSF, which is most often associated with the treatment of residuals from coal combustion and inert waste, is less suitable for international comparative studies, as the regionalization of these processes is not available outside of Europe. In future studies, regionalization needs to be advanced and substances other than aluminum need to be considered to increase the usability of this promising tool.

Moreover, some conclusions for the case studies can be drawn from the analyses of the environmental impacts:

1. Apart from its other environmental impacts, coal-fired electricity has a high fossil energy demand due to the energy dependence of coal mining and related processes, which exceeds the yield significantly. This is another hint that a shift away from fossil fuels should be accelerated.
2. Small, decentralized forms of hydropower also have environmental impacts. The case study at the Danube revealed a high WSF_{quan}. Even if the data is associated with high uncertainties (see Appendix 1), the possible effects should not be ignored in advance, but rather examined and validated in detail for any hydropower case study." The same is true for the impacts on aquatic ecosystems.
3. The CSP is responsible for high impacts related to the construction phase. As already pointed out before, measures to reduce the raw material requirements as well as options to promote supply from reuse or recycling should already be evaluated during the planning phase to reduce environmental impacts.

Biomass is only conditionally suitable for sustainable electricity generation. It is important to emphasize here, that our associated partner in Brazil explicitly uses bagasse as waste. However, through the comparison with the reference-product-model the transferability of this study increases in an international context. It leads to the clear statement that biomass for electricity production is only environmentally friendly if waste biomass is used. If biomass is explicitly produced for the purpose of electricity generation, the environmental impacts even surpass the impacts from coal combustions by far. Furthermore, the burning of biomass is related to additional on-site impacts as compared to the combustion of coal. At this point, it is necessary to investigate whether these impacts can be further reduced with modern technologies and to what extent non-use of the waste biomass produced is also associated with environmental impacts.

3.6 References Chapter 3

The Cambridge Handbook of Stakeholder Theory. (2018).

50Hertz Transmission GmbH. (2021, June 28). *regelleistung.net*. https://www.regelleistung.net/ext/static/technical

Adam, W. C. (2015). *Handbook of practical program evaluation: Chapter 19: Conducting Semi-Structured Interviews* (Fourth edition). *Essential texts for nonprofit and public leadership and management*. Jossey-Bass & Pfeiffer Imprints, Wiley.

Agência Nacional de Águas. (n.d). *Qualiágua*. Retrieved May 17, 2021, from http://portalpnqa.ana.gov.br/Qualiagua.aspx

Agência Nacional de Águas. (2005). *Hidroweb V.2.0.0.0*. http://www.snirh.gov.br/hidroweb/publico/medicoes_historicas_abas.jsf,

Agência Nacional de Águas. (2007). *Unidades de Planejamento Hídrico*. http://metadados.ana.gov.br/geonetwork/srv/pt/main.home

Agência Nacional de Águas. (2013). *Base Hidrográfica Ottocodificada Multiescalas 2013: Rios*. Publication bibliography

Agência Nacional de Águas. (2017). *Projeto Legado*. https://www.gov.br/ana/pt-br/programas-e-projetos/projeto-legado-1/projeto-legado/documento-base-versao-1-0-6-dezembro-2017.pdf

Agência Nacional de Águas. (2019). *Outorga dos direitos de uso de recursos hídricos*. Brasilia. Agência Nacional de Águas (ANA). http://www.snirh.gov.br/portal/snirh/centrais-de-conteudos/conjuntura-dos-recursos-hidricos/ana_encarte_outorga_conjuntura2019.pdf

Agência Nacional de Águas - ANA. (2021, June 29). *Portal da Qualidade das Águas*. http://portalpnqa.ana.gov.br/Qualiagua.aspx

Ahlborg, H., Ruiz-Mercado, I., Molander, S., & Masera, O. (2019). Bringing Technology into Social-Ecological Systems Research—Motivations for a Socio-Technical-Ecological Systems Approach. *Sustainability*, *11*(7), 2009. https://doi.org/10.3390/su11072009

Albrecht, T. R., Crootof, A., & Scott, C. A. (2018). The Water-Energy-Food Nexus: A systematic review of methods for nexus assessment. *Environmental Research Letters*, *13*(4), 43002. https://doi.org/10.1088/1748-9326/aaa9c6

Albrecht, T. R., Crootof, A., & Scott, C. A. (2018). The Water-Energy-Food Nexus: A systematic review of methods for nexus assessment. *Environmental Research Letters*, *13*(4), 43002. https://doi.org/10.1088/1748-9326/aaa9c6

ARRUDA, M. R. de, Giller, K. E., & SLINGERLAND, M. (2017). Where is sugarcane cropping expanding in the brazilian cerrado, and why? A case study. *Anais Da Academia Brasileira De Ciências*, *89*(3 Suppl), 2485–2493. https://doi.org/10.1590/0001-3765201720150260

B.A.U.M. Consult GmbH. 2013. (2021, June 28). *Klimaschutzkonzept*. https://landkreis.neu-ulm.de/de/klimaschutzkonzept/klimaschutzkonzept-20001122.html

Bauer, N., Calvin, K., Emmerling, J., Fricko, O., Fujimori, S., Hilaire, J., Eom, J., Krey, V., Kriegler, E., Mouratiadou, I., Sytze de Boer, H., van den Berg, M., Carrara, S., Daioglou, V., Drouet, L., Edmonds, J. E., Gernaat, D., Havlik, P., Johnson, N., . . . van Vuuren, D. P. (2017). Shared Socio-Economic Pathways of the Energy Sector – Quantifying the Narratives. *Global Environmental Change*, *42*, 316–330. https://doi.org/10.1016/j.gloenvcha.2016.07.006

Bayerisches Staatsministerium für Wirtschaft, Landesentwicklung und Energie. (2021, June 28). *Energie-Atlas Bayern - Wasser - Daten und Fakten*. Bayerisches Staatsministerium für Wirtschaft, Landesentwicklung und Energie. https://www.energieatlas.bayern.de/thema_wasser/daten.html

Bielicki, J. M., Beetstra, M. A., Kast, J. B., Wang, Y., & Tang, S. (2019). Stakeholder Perspectives on Sustainability in the Food-Energy-Water Nexus. *Frontiers in Environmental Science*, *7*, Article 7, 7. https://doi.org/10.3389/fenvs.2019.00007

Bundesministeriumm für Wirtschaft und Energie. (2021, June 28). *Deutsche Klimaschutzpolitik.* BMWI. https://www.bmwi.de/Redaktion/DE/Artikel/Industrie/klimaschutz-deutsche-klimaschutzpolitik.html

Bundesregierung. (2021, June 28). *Ausstieg aus der Kernkraft.* https://www.bundesregierung.de/breg-de/themen/energiewende/energie-erzeugen/ausstieg-aus-der-kernkraft-394280

Cagnova. (2021, June 28). *JRC Publications Repository - Global Energy and Climate Outlook 2017: How climate policies improve air quality*. https://publications.jrc.ec.europa.eu/repository/handle/JRC107944

Camporez, P. (2020). *Especial Guerra das Águas: Rios vigiados, Rios roubados, Rios mortos, Rios vigiados*. https://www.estadao.com.br/infograficos/politica,rios-vigiados,1063363

Camporez, P., / Fotos e vídeos: Dida Sampaio (2020, February 2). Rios vigiados. *Estadão*. https://www.estadao.com.br/infograficos/politica,rios-vigiados,1063363

Campos Zeballos, J., Sebesvari, Z., Rhyner, J., Metz, M., & Bufon, V. B. (2021). Drought risk assessment of sugarcane-based electricity generation in the basin Rio dos Patos basin, Brazil [*Manuscript in Preparation]*.

Cundill, G., & Rodela, R. (2012). A review of assertions about the processes and outcomes of social learning in natural resource management. *Journal of Environmental Management*, *113*, 7–14. https://doi.org/10.1016/j.jenvman.2012.08.021

Da Silva, F., de Moraes, J., Vilela, M., Cesar, M., & Mendes, C. (2011). Diagnóstico hídrico em destilarias de álcool em São Paulo, *1*(1). https://ainfo.cnptia.embrapa.br/digital/bitstream/item/39538/1/18-46-1-PB.pdf

de Oliveira Domingues, W. S. (07.2018). Interview by T. Landwehr, & J. Campos Zeballos. Goiás, Brasil.

Deutsches Institut für Entwicklungspolitik. (2021, June 28). *Post 2015: why is the water-energy-land nexus important for the future development agenda?* https://www.die-gdi.de/briefing-paper/article/post-2015-why-is-the-water-energy-land-nexus-important-for-the-future-development-agenda/

Edenhofer, O., Pichs Madruga, R., Sokona, Y., Syboth, K., Matschoss, P., Kadner, S., Zwickel, T., Eickemeier, P., Hansen, G., Schlömer, S., & von Stechow, C. (2012). *Renewable energy sources and climate change mitigation: Special report of the Intergovernmental Panel on Climate Change / edited by Ottmar Edenhofer [and ten others]*. Cambridge University Press.

Empresa Brasileira de Pesquisa Agropecuária. (2018). *Precipitation data*.

Energie- und Umweltzentrum Allgäu. *Landkreis Dillingen a.d. Donau – Energie- und CO¬2-Bilanz 2016*.

European Commission. Joint Research Centre. (2017). *Global energy and climate outlook 2017: How climate policies improve air quality: Global energy trends and ancillary benefits of the Paris Agreement*. Publications Office. https://doi.org/10.2760/474356

Félix, A. (06.2018). Interview by T. Landwehr, J. Campos Zeballos, & A. F. Domingues. Brasilia, Brasil.

Félix, A. (06.2020). Interview by F. Kastrup, & A. F. Domingues. Brasilia, Brasil.

FOREST - GIS. *Principais Rios do Brasil*. http://forest-gis.com/download-de-shapefiles/

ForestGIS.com | O seu portal de geotecnologia. (2021, June 18). *Download de Shapefiles e bases de dados GIS*. https://forest-gis.com/download-de-shapefiles/

Forum Nacional Sucroenergético, & União da Indústria de Cana-de-Açúcar. (2014). *Gestão dos Recursos Hídricos na Agroindústria Canavieira.* União da Indústria de Cana-de-Açúcar; Confederação Nacional da Indústria. https://unica.com.br/wp-content/uploads/2019/06/Gestao-dos-Recursos-Hidricos.pdf

Freitas, M. (06.2018). Interview by T. Landwehr, & J. Campos Zeballos. Brasilia, Brasil.

GADM. (2018). *Country administrative areas: GADM data (version 3.6)*. https://gadm.org/download_country_v3.html

Greenpeace. (2015). *Energy [r] evolution-a sustainable world energy outlook*.

Hagemann, N., & Kirschke, S. (2017). Key Issues of Interdisciplinary NEXUS Governance Analyses: Lessons Learned from Research on Integrated Water Resources Management. *Resources*, *6*(1), 9. https://doi.org/10.3390/resources6010009

Hayley Leck, D. Conway, M. Bradshaw, & J. Rees (2015). Tracing the water-energy-food nexus: description, theory and practice. *Undefined*. https://www.semanticscholar.org/paper/Tracing-the-water-energy-food-nexus%3A-description%2C-Leck-Conway/32a629dec93c34fb30cdb517f96b1b512d4532ba

Hoolohan, C., Larkin, A., McLachlan, C., Falconer, R., Soutar, I., Suckling, J., Varga, L., Haltas, I., Druckman, A., Lumbroso, D., Scott, M., Gilmour, D., Ledbetter, R., McGrane, S., Mitchell, C., & Yu, D. (2018). Engaging stakeholders in research to address water-energy-food (WEF) nexus challenges. *Sustainability Science*, *13*(5), 1415–1426. https://doi.org/10.1007/s11625-018-0552-7

IEA/OECD. (2021, June 28). *World Energy Outlook 2017 – Analysis - IEA*. https://www.iea.org/reports/world-energy-outlook-2017

Instituto Nacional de Meteorologia. *Banco de Dados Meteorológicos para Ensino e Pesquisa (BDMEP)*. http://www.inmet.gov.br/portal/index.php?r=bdmep/bdmep

Intergovernmental Panel on Climate Change. (2014). *Climate change 2014: Impacts, adaptation and vulnerability / edited by Christopher B. Field, Working Group II Co-Chair, Department of Global Ecology, Carnegie Institution for Science, Vicente R. Barros, Working Group II Co-Chair, Centro de Investigaciones del Mar y la Atmósfera, Universidad de Buenos Aires [and 14 others]* (Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir,M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy,S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press.

International Energy Agency - IEA. *World Energy Outlook 2016 - Excerpt - Water-Energy Nexus*.

IRENA. (2021, June 28). *Renewable Energy in the Water Energy: Food Nexus*. https://www.irena.org/publications/2015/Jan/Renewable-Energy-in-the-Water-Energy--Food-Nexus

Jin, Y., Behrens, P., Tukker, A., & Scherer, L. (2019). Water use of electricity technologies: A global meta-analysis. *Renewable and Sustainable Energy Reviews*, *115*, 109391. https://doi.org/10.1016/j.rser.2019.109391

Kitous, A., Keramidas, K., Vandyck, T., Saveyn, B., van Dingenen, R., Spadaro, J. V., & Holland, M. (2017). *Global energy and climate outlook 2017: How climate policies improve air quality: Global energy trends and ancillary benefits of the Paris Agreement*. *JRC science for policy report*. Publications Office of the European Union. https://www.researchgate.net/publication/321442798_Global_Energy_and_Climate_Outlook_2017_How_climate_policies_improve_air_quality_-_Global_energy_trends_and_ancillary_benefits_of_the_Paris_Agreement https://doi.org/10.2760/474356

Köhler, J., Rödl, A., & Kaltschmitt, M. (2020, April 23). *Treibhausgasemissionen von Strom aus Wasserkraft*. https://www.springerprofessional.de/treibhausgasemissionen-von-strom-aus-wasserkraft/17920822

Krumme, K. (2016). Sustainable Development and Social-Ecological-Technological Systems (SETS): Resilience as a Guiding Principle in the Urban-Industrial Nexus. *Renewable Energy and Sustainable Development*, *2*(2), 70–90. https://doi.org/10.21622/RESD.2016.02.2.070

Landkreis Günzburg. 2015. *Vorstellung von Klimaschutz- und Energiefakten für den Landkreis Günzburg und seine Gemeinden*.

Leal, M., Duft, D. G., Hernandes, T., & Bordonal, R. O. (2017). Brazilian Sugarcane Expansion and Deforestation (Conference: 25th European Biomass Conference and Exhibition).

LEW. (2021, June 28). *Wasserkraft an Flüssen in Bayerisch-Schwaben | LEW Wasserkraft*. https://wasserkraft.lew.de/lew-wasserkraft/unsere-wasserkraftwerke/standorte

Lima, J. E. F. W. (06.2018). Interview by T. Landwehr, & J. Campos Zeballos.

Lucy Stevens, & Mary Gallagher. (2015). The Energy–Water–Food Nexus at Decentralized Scales. In L. Stevens & M. Gallagher (Eds.), *Poor people's energy briefing: Vol. 3. The energy-water-food nexus at decentralized scales: Synergies, trade-offs, and how to manage them* (pp. 1–15). Practical Action Publishing. https://www.researchgate.net/publication/300229488_The_Energy-Water-Food_Nexus_at_Decentralized_Scales

Lumosi, C. K., Pahl-Wostl, C., & Scholz, G. (2019). Can 'learning spaces' shape transboundary management processes? Evaluating emergent social learning processes in the Zambezi basin. *Environmental Science & Policy*, *97*, 67–77.

Magrineli, A. (06.2020). Interview by F. Kastrup.

MapBiomas. (2017). *Land Cover Data: Semi-Perennial Crop*. http://mapbiomas.org/map#coverage

Markolf, S. A., Chester, M. V., Eisenberg, D. A., Iwaniec, D. M., Davidson, C. I., Zimmerman, R., Miller, T. R., Ruddell, B. L., & Chang, H. (2018). Interdependent Infrastructure as Linked Social, Ecological, and Technological Systems (SETSs) to Address Lock-in and Enhance Resilience. *Earth's Future*, *6*(12), 1638–1659. https://doi.org/10.1029/2018EF000926

McBride, M. F., Lambert, K. F., Huff, E. S., Theoharides, K. A., Field, P., & Thompson, J. R. (2017). Increasing the effectiveness of participatory scenario development through codesign. *Ecology and Society*, *22*(3). https://doi.org/10.5751/ES-09386-220316

Mohtar, R. H., & Lawford, R. (2016). Present and future of the water-energy-food nexus and the role of the community of practice. *Journal of Environmental Studies and Sciences*, *6*(1), 192–199. https://doi.org/10.1007/s13412-016-0378-5

Mundialis. (2020). *Current and future potential sugarcane expanssion shapefile.*

Narvaez Marulanda, B. L., Campos Zeballos, J., Janzen, S., Sebesvari, Z., Bufon, V. B., & Sandholz, S. (2021). Applying a Social-Ecological-Technological approach to vulnerability assessments: the case of sugarcane-based electricity generation under drought conditions in Rio dos Patos, Brazil [Manuscript in preparation].

Neto, A. E. *Management of Water Resources in the Sugarcane Agro-Industry in Brazil: Workshop on "Examples of Positive Bioenergy and Water Relationships"*. Royal Swedish Academy of Agriculture and Science (KSLA). http://www.globalbioenergy.org/fileadmin/user_upload/gbep/docs/2015_events/AG6_workshop_25-26_August_2015/25_Aug_7_Elia.pdf

Newcomer, K. (2015). *Handbook of practical program evaluation* (Fourth edition). *Essential texts for nonprofit and public leadership and management*. Jossey-Bass a Wiley Imprint. http://worldcatlibraries.org/wcpa/oclc/922625512

novaCana. (n.d). *Usinas de açúcar e álcool no estado: Goiás: Goiás: lista das unidades em operação*. Retrieved January 27, 2021, from https://www.novacana.com/usinas_brasil/estados/goias

novaCana. (2018). *O setor sucroenergético visto a partir de 12 mapas do IBGE*. https://www.novacana.com/n/cana/safra/setor-sucroenergetico-12-mapas-ibge-240718

Organisation for Economic Co-operation and Development. (2015). *Water Resources Governance in Brazil*. OECD. https://doi.org/10.1787/9789264238121-en

Paul C Godfrey, & Ben William Lewis. (2018). Pragmatism and Pluralism: A moral foundation for stakeholder theory in the 21 st Century. In *The Cambridge Handbook of Stakeholder Theory.* https://www.researchgate.net/publication/325128510_Pragmatism_and_Pluralism_A_moral_foundation_for_stakeholder_theory_in_the_21_st_Century

Presidência da República. (2021, June 29). *LEI Nº 9.433, DE 8 DE JANEIRO DE 1997.* http://www.planalto.gov.br/ccivil_03/leis/l9433.htm

Project MapBiomas. (2018). *Collection 3.1 of Brazilian Land Cover & Use Map Series: Cerrados Biome 2017*. https://code.earthengine.google.com/?accept_repo=users/mapbiomas/user-toolkit "

Reisinger, A., Howden, M., Vera, C., Garschagen, M., Hurlbert, M., Kreibiehl, S., Mach, K. J., Mintenbeck, K., O'Neill, B., Pathak, M., Pedace, R., Pörtner, H.-O., Poloczanska, E., Rojas Corradi, M., Sillmann, J., van Aalst, M., Viner, D., Jones, R., Ruane, A. C., & Ranasinghe, R. (2020). *The Concept of Risk in the IPCC Sixth Assessment Report: A Summary of Cross-Working Group Discussions: Guidance for IPCC authors.* Intergovernmental Panel on Climate Change (IPCC). https://www.ipcc.ch/site/assets/uploads/2021/02/Risk-guidance-FINAL_15Feb2021.pdf

Republic of Kenya. *Final SE4ALL AA Kenya January 2016[2]*.

Lei Nº 9.433, de 8 de Janeiro de 1997., January 8, 1997. http://www.planalto.gov.br/ccivil_03/leis/l9433.htm

RESOLUÇÃO CONAMA. *Resolução CONAMA N° 357*. March 17, 2005.

RESOLUÇÃO N° 09. *Resolucao 2005*. http://www.sgc.goias.gov.br/upload/arquivos/2015-10/resolucao-ndeg09_04-de-maio-de-2005.pdf

RESOLUÇÃO N° 11. *Resolucao 2007*. https://www.meioambiente.go.gov.br/images/imagens_migradas/upload/arquivos/2015-10/resolucao-ndeg11_20-de-marco-de-2007.pdf

Rötz, A., Theobald, S. 2019. Model-Based Operation of Multi-Purpose River and Reservoir Systems. *Water Resources Management. 30* (15) S. 4969-4982.

Rudorff, B. F. T., Aguiar, D. A., Silva, W. F., Sugawara, L. M., Adami, M., & Moreira, M. A. (2010). Studies on the Rapid Expansion of Sugarcane for Ethanol Production in São Paulo State (Brazil) Using Landsat Data. *Remote Sensing*, *2*(4), 1057–1076. https://doi.org/10.3390/rs2041057

Scarpare, F. V., Hernandes, T. A. D., Ruiz-Corrêa, S. T., Picoli, M. C. A., Scanlon, B. R., Chagas, M. F., Duft, D. G., & Cardoso, T. d. F. (2016). Sugarcane land use and water resources assessment in the expansion area in Brazil. *Journal of Cleaner Production*, *133*, 1318–1327. https://doi.org/10.1016/j.jclepro.2016.06.074

Scarpare, F. V., Hernandes, T. A. D., Ruiz-Corrêa, S. T., Picoli, M. C. A., Scanlon, B. R., Chagas, M. F., Duft, D. G., & Cardoso, T. d. F. (2016). Sugarcane land use and water resources assessment in the expansion area in Brazil. *Journal of Cleaner Production*, *133*(5), 1318–1327. https://doi.org/10.1016/j.jclepro.2016.06.074

Secretaria de Estado de Meio Ambiente e Desenvolvimento Sustentável. (2020). *Outorgas do uso da água*. Goiás, Brasil.

Sistema Estadual de Geoinformação. (2004). *Recursos Hídricos - Bacias Hidrográficas: Goiás State*. http://www.sieg.go.gov.br/siegdownloads/

Sistema Estadual de Geoinformação. (2006). *Base Cartografica: Drenages*. http://www.sieg.go.gov.br/siegdownloads/

Steffen, B., Hischier, D., & Schmidt, T. (2018). *Current and future energy performance of power generation technologies in Switzer-land*.

Stevens, L., & Gallagher, M. (Eds.). (2015). *Poor people's energy briefing: Vol. 3. The energy-water-food nexus at decentralized scales: Synergies, trade-offs, and how to manage them*. Practical Action Publishing.

Strasser, L. de, Lipponen, A., Howells, M., Stec, S., & Bréthaut, C. (2016). A Methodology to Assess the Water Energy Food Ecosystems Nexus in Transboundary River Basins. *Water*, *8*(2), 59. https://doi.org/10.3390/w8020059

Superintendência de Recursos Hídricos. (2012). *Manual Técnico de Outorga: 1a versão.* Governo de Goias. http://www.sgc.goias.gov.br/upload/arquivos/2015-07/manual_tecnico_de_outorga_versao_01.pdf

Terrapon-Pfaff, J., Ersoy, S. R., Fink, T., Amroune, S., Jamea, E. M., Zgou, H., & Viebahn, P. (2021). Localizing the Water-Energy Nexus: The Relationship between Solar Thermal Power Plants and Future Developments in Local Water Demand. *Sustainability*, *13*(1), 108. https://doi.org/10.3390/su13010108

Terrapon-Pfaff, J., Ortiz, W., Dienst, C., & Gröne, M.-C. (2018). Energising the WEF nexus to enhance sustainable development at local level. *Journal of Environmental Management*, *223*, 409–416. https://doi.org/10.1016/j.jenvman.2018.06.037

Terrapon-Pfaff, J., Ortiz, W., Viebahn, P., Kynast, E., & Flörke, M. (2020). Water Demand Scenarios for Electricity Generation at the Global and Regional Levels. *Water*, *12*(9), 2482. https://doi.org/10.3390/w12092482

Theobald, S. (1999). *Numerische Simulation von Staustufenketten mit automatisiertem Betrieb*. BibTeX.

Theobald, U., & Theobald, S. (2011). Central Water Resources Management in a cascade of hydropower plants. *IEEE International Conference on Networking, Sensing and Control*.

Thomas Andre, & Flávia Guerra. (2020). *Renewables 2020 Global Status Report*. https://www.researchgate.net/publication/342380245_Renewables_2020_Global_Status_Report

Umweltbundesamt. (2021). *Energieverbrauch privater Haushalte*.

United Nations 2015. *Transforming our world: the 2030 agenda for sustainable develop- ment. Working papers*.

United Nations Convention to Combat Desertification. *Land and Drought*. https://www.unccd.int/issues/land-and-drought

van der Leer, J., van Timmeren, A., & Wandl, A. (2018). Social-Ecological-Technical systems in urban planning for a circular economy: An opportunity for horizontal integration. *Architectural Science Review*, *61*(5), 298–304. https://doi.org/10.1080/00038628.2018.1505598

World Bank Group. *World Bank Document*.

WWAP 2019. (2019). *Leaving no one behind. The United Nations world water development report: Vol. 2019*. Unesco. https://en.unesco.org/themes/water-security/wwap/wwdr/2019

4 Global Scenario Analysis

4.1 Meta-Study on Energy Scenarios

Authors: Julia Terrapon-Pfaff, Peter Viebahn, Sibel Raquel Ersoy

Water and energy are of central importance for sustainable development globally and in Germany. At the same time, there are many links between water and energy supply, so that developments and decisions in one sector can have a direct or indirect impact on the other. Especially in view of the restructuring of the global energy supply, possible trade-offs and synergies between water resources and energy production should be investigated on a global and regional level.

The energy sector today accounts for about 10% to 15% of global freshwater withdrawal, and for about 3% of total water consumption (OECD/IEA, 2016; IRENA, 2015). Most water in the energy sector is used for generating electricity (about 88%), especially for cooling processes in thermal power plants (thermal power plants account for about 70% of today's global installed power plant capacity (OECD/IEA, 2016)). At the same time the demand for electricity is expected to increase significantly due to population growth and economic development in emerging and developing economies, growing demand is also driven by electrification strategies pursued by industrialized countries to decarbonize their economies (Bauer et al., 2017). With the global demand for electricity expected to increase significantly in the coming decades also the water demand in the power sector is expected to rise. However, due to the on-going global energy transition, the future structure of the power supply – and hence future water demand for power generation – is subject to high levels of uncertainty because the volume of water required for electricity generation varies significantly depending on both the generation technology and cooling system. And even assuming rapid decarbonization of the energy sector, the development of future water demand for electricity generation remains unclear because different renewable energy and climate protection technologies also have very different water use intensities (Jin et al., 2019).

In light of these challenges the objective of this analysis is to provide more systematic and robust answers in terms of the impacts of different decarbonization strategies in the electricity sector on water demand at global and regional level. The focus is on operational water use for electricity generation. The first step was to determine in which countries or regions the technologies in question are already widespread or where they are to be expanded in the future. To this end, a meta-analysis of existing long-term energy scenarios was conducted.

The time horizon was set to 2040 based on the data availability in the analyzed energy scenarios. In a second step, demand-side water scenarios are created by coupling the determined installed capacity of the technologies under consideration with their water consumption, so that the water consumption per year and region can be represented. To do so a set of future scenarios was designed by combining decision options in two technological fields: a) types of electricity generation technologies; and b) types of cooling technologies. In the third step, the water withdrawal and consumption levels of the different technological pathways are calculated for each region up to 2040, resulting in water demand scenarios for different electricity futures and making it possible to identify the most water-efficient transition pathways for the electricity sector.

4.1.1 Research approach

The water demand for electricity generation depends mainly on three key parameters: (a) the mix of energy sources and type of generation technologies applied; (b) the type of cooling technology deployed at thermal power plants; and (c) the water use intensity in form of specific water withdrawal and consumption levels for each combination of electricity generation technology and cooling technology. To determine the future water requirements of the power sector, these three parameters are first assessed individually and then combined to estimate the water demand of the electricity sector according to different given future energy scenarios. The approach is summarized in Figure 4-1.

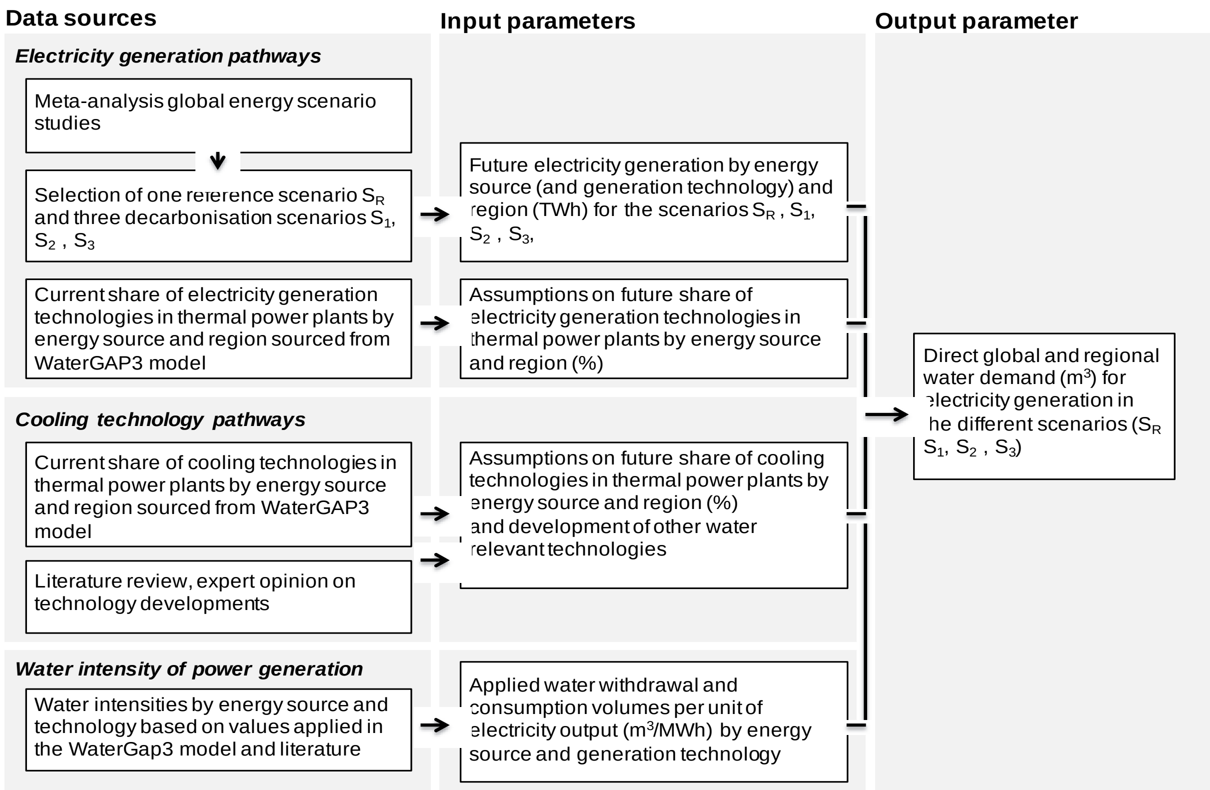

Figure 4-1: Overview of methodology applied to estimate water demand for different electricity generation pathways (Terrapon-Pfaff et al., 2020).

4.1.2 Meta-analysis global energy scenario studies

As a result of the comparative literature review, one reference scenario (IEA CP) and three decarbonization scenarios were chosen based on their heterogeneity in terms of energy transition strategies and their ambition levels in terms of greenhouse gas emission reductions, i.e. in line with, or at least close to, the target of limiting the global temperature increase to "below 2°C" (Table 4-1). This allows for comparisons to be made concerning the impact on water demand arising from major shifts in the electricity sector required to achieve these climate objectives.

Table 4-1: Overview of selected energy scenarios (Terrapon-Pfaff et al. 2020)

Study	**Time horizon**	**Scenario**	**GHG-changes 2040** (compared to 1990)	**Summary strategies**
World Energy Outlook (IEA/OECD 2017)	2040	**Reference scenario:** IEA | Current Policies (CP)	+104%	• Assessment of energy sector development in the absence of any additional measures
		IEA | Sustainable Development (SD)	-13%	• Back-casting approach • Stronger role of renewable energies • Broad exploitation of efficiency potentials in the industrial sector • Transport sector: increasing electrification and increasing use of ("advanced") biofuels and natural gas assumed • Carbon capture and storage (CCS)
The advanced energy [r]evolution (Greenpeace 2015)	2050	GP | Advanced Energy Revolution (Ad.[R])	-61%	• Renewable electricity as the most important primary energy resource • Limited use of biomass (100 EJ/a) • Broad electrification of the transport sector • Hydrogen and other synthetic fuels in sub-sectors difficult to electrify (e.g. freight transport) • No carbon capture and storage (CCS) • Phase-out of nuclear energy
Global Energy and Climate Outlook (JRC 2017)	2050	GECO | B2°C	+1%	• Combination of carbon capture and storage (CCS) , renewables and nuclear power in the electricity sector • In the transport sector: combination of electricity, biofuels, natural gas and hydrogen

The comparison of transition pathways for the electricity sector show that all the scenarios anticipate an increase in electricity generation by 2040 compared to 2015 (Figure 4-2). However, the extent of the increase and the overall mix of energy sources vary considerably depending on the scenario. The different underlying decarbonization strategies and the level of ambition in respect to GHG emissions reductions explain these differences. For example, scenarios assuming a higher degree of electrification in sectors such as transport or industry require higher amounts of electricity. Moreover, assumptions about economic development and population growth underlying the energy scenarios can influence the anticipated total future electricity demand. Unsurprisingly, all the scenarios expect an increase in electricity generation from renewable energy sources, with wind and photovoltaic anticipated to increase the most.

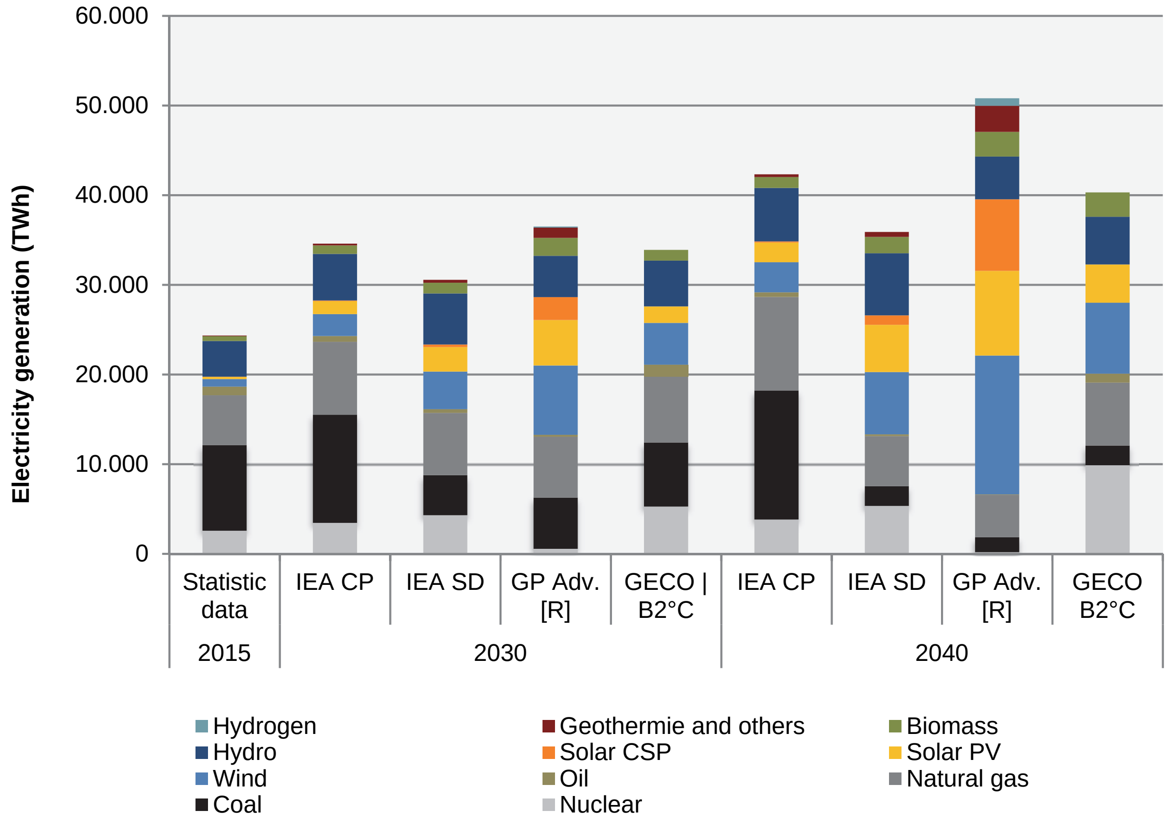

Figure 4-2: Electricity generation by energy source (in TWh) for the year 2015 and the four selected energy scenarios in 2030 and 2040 (Terrapon-Pfaff et al., 2020. Based on data from IEA/OECD, 2017; Greenpeace, 2015; JRC, 2017).

4.1.3 Modeling future water demand for electricity generation

These differences in the electricity mix influence both the water withdrawal and consumption of future electricity systems. The changes in future global water withdrawal vary between +55% and -72% compared to 2015 (Figure 4-3). Overall, higher shares of fossil fuels are likely to lead to greater water withdrawal, while scenarios with high shares of renewable energies perform better in terms of reducing future water withdrawal. This is due to the fact that electricity generated from fossil fuels still comes predominantly from thermoelectric power plants based on technologies with higher water withdrawal intensities.

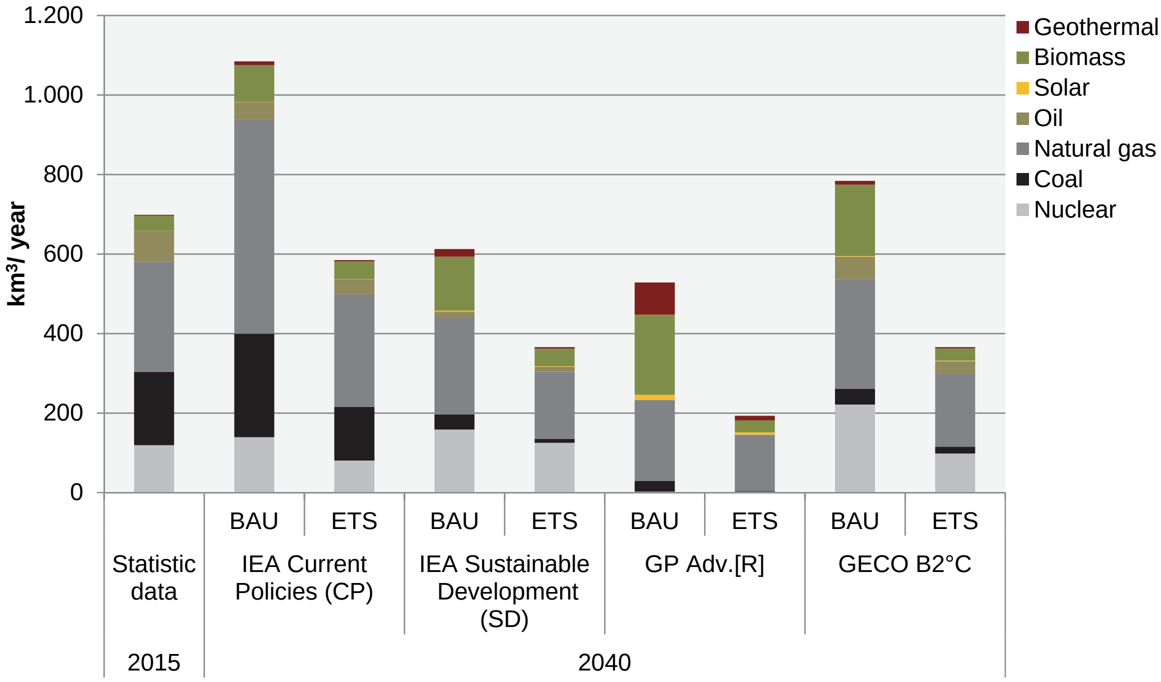

Figure 4-3: Water withdrawal (in km³ per year) for electricity generation by energy source for different scenarios in 2040 (Terrapon-Pfaff et al., 2020. Based on data from IEA/OECD, 2017; Greenpeace, 2015; JRC, 2017).

In term of global water consumption for electricity generation it is shown that water consumption is expected to rise in five out of eight scenarios (by between 9% and 78%) compared to 2015. The increase in global water consumption occurs as a result of an increase in electricity production and a shift towards improved cooling systems, which withdraw less water but consume more (Figure 4-4). Furthermore, the widescale implementation of thermal renewable energy technologies such as geothermal, biomass and concentrated solar power (CSP) compared to solar photovoltaic or wind can lead to an increase in water consumption from the renewable energy side. From a global perspective, it can be concluded that more efficient cooling and electricity generation systems (i.e., ETS scenarios) can significantly reduce the water demand of the power sector in terms of water withdrawal and consumption.

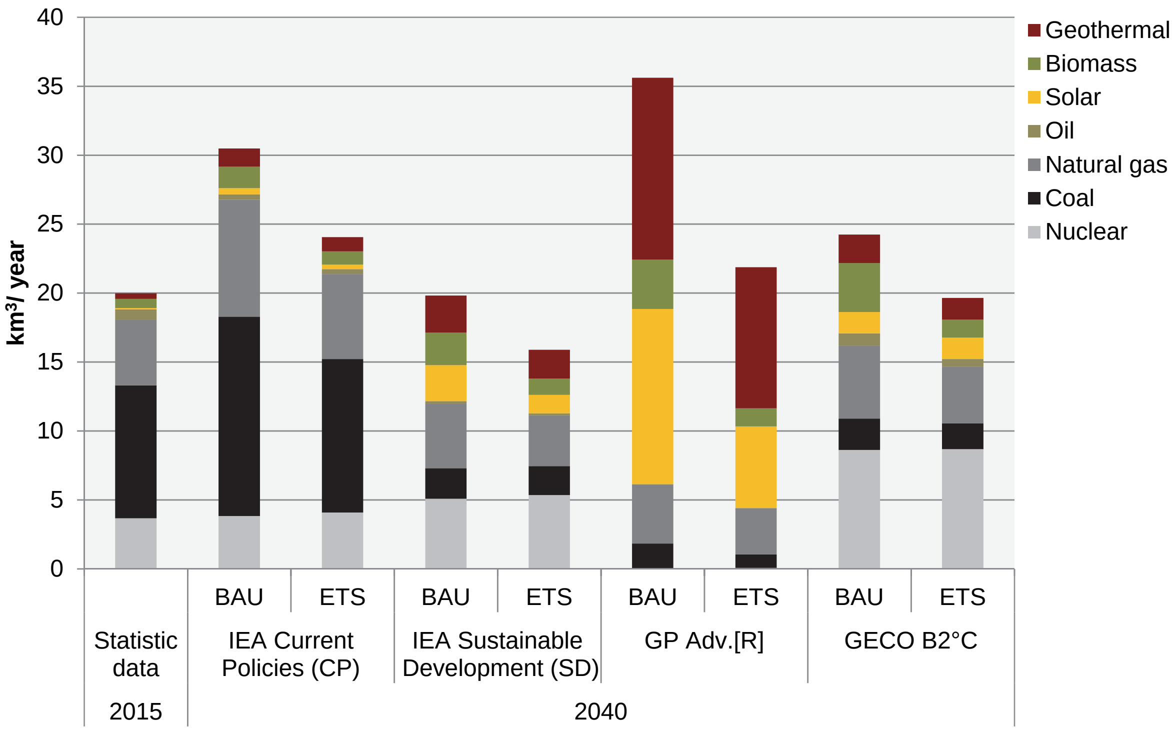

Figure 4-4: Water consumption (in km³ per year) for electricity generation by energy source for different scenarios in 2040 (Terrapon-Pfaff et al., 2020. Based on data from IEA/OECD, 2017; Greenpeace, 2015; JRC, 2017).

At the regional level, the analysis focuses on the development of water demand for power generation in ten regions. The shifts in electricity generation expected in the scenarios lead in part to very different regional developments. North America is the only region that shows a consistent reduction in water withdrawals (5% to 74%) across all scenarios. Despite this decrease, North America remains the region with the highest share of global water withdrawals (20% to 28%) in six of eight scenarios. A decrease in water withdrawal is also observed in most scenarios for Europe, Eastern Europe and Eurasia, and Asia-Oceania-OECD. On the other hand, the developing and emerging regions, namely China, India, Asia (other), the Middle East, Latin America, and Africa, are characterized by an increase in water withdrawals for electricity generation in the scenarios with higher shares of fossil fuels. Overall, the results indicate that it is particularly important for developing and emerging regions to combine the expansion of energy supply with less water-intensive technologies, including in particular renewable energy technologies such as photovoltaics and wind energy, in order to reduce water demand for electricity generation. The results for water consumption also differ markedly across the regions (Figure 4-5) depending on the scenario. In North America, four of the scenarios result in reduced water consumption by 11% to 31%, while four predict an increase of 1% to 11%. In Europe, seven scenarios predict a reduction in water consumption which can mainly be attributed to the decrease of coal and oil in the electricity mix and to the phase-out of nuclear energy. The water consumption for renewable electricity generation increases in Europe in all scenarios but remains lower than the use of water for fossil power generation in 2015 in seven out of the eight scenarios. Scenario results also show large variations in water consumption for future electricity generation in China. In India, Asia (Other), the Middle East, Latin America and Africa, the growth in water consumption is substantial in all scenarios except one. The rise in water consumption in these regions is mainly driven by the rapid growth in electricity demand. In terms of technologies, natural gas, biomass, solar and nuclear energy, are the main drivers for the increase in water consumption in these regions.

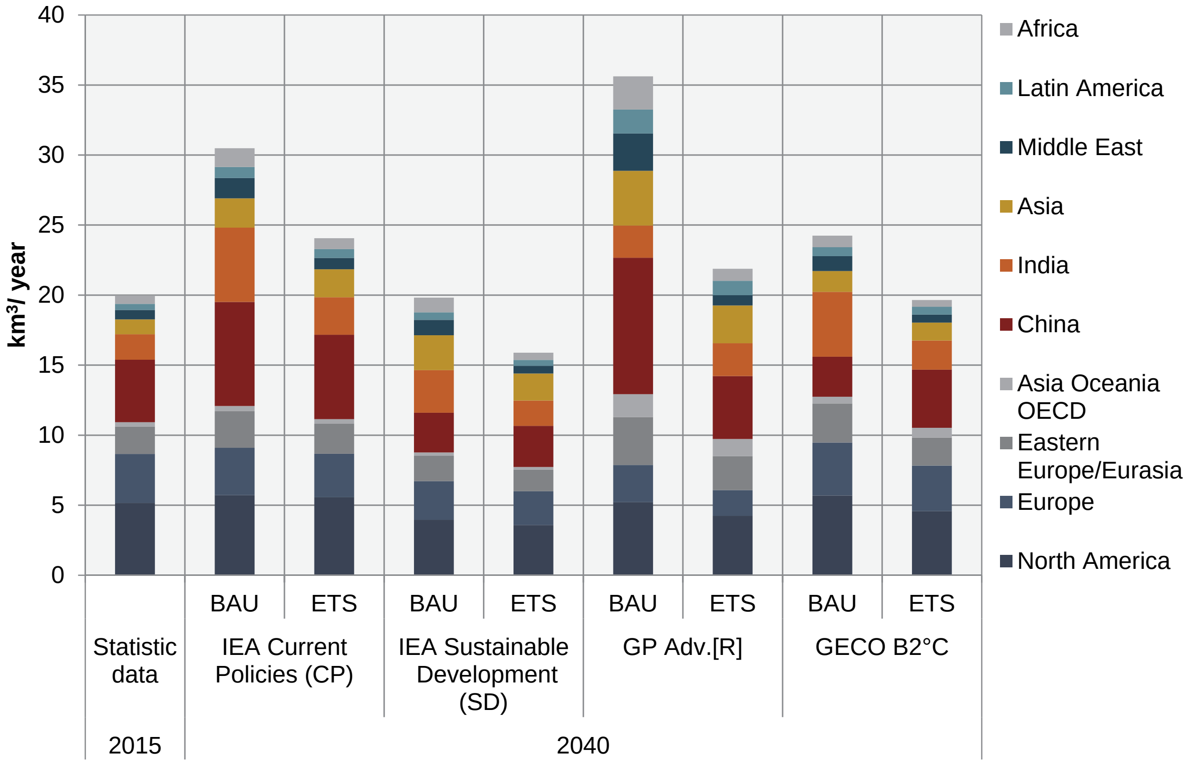

Figure 4-5: Water consumption for electricity generation (in km3 per year) by region for different scenarios in 2040 (Terrapon-Pfaff et al., 2020. Based on data from IEA/OECD, 2017; Greenpeace, 2015; JRC, 2017).

The results show that water demand varies significantly between different electricity mixes. Ambitious decarbonization scenarios with extensive use of renewables and high electrification rates in key energy-intensive sectors have the lowest water intensities, but in absolute terms these systems may result in higher water use than the less ambitious climate change mitigation scenarios. The results underline the importance of considering not only the potential to reduce greenhouse gas emissions but also other environmental aspects - such as water demand - when designing future electricity systems to ensure a holistically sustainable energy transition.

4.2 Land Use Change Scenarios

Authors: Christopher Jung, Rüdiger Schaldach, Ellen Kynast

4.2.1 Modelling approach

Land use change can have important impacts on the environment as well as human society. It affects biodiversity, the provision of ecosystem services, biogeochemical and hydrological cycles. Also, socio-economic conditions are affected, such as labor opportunities, trading possibilities and thereby the size of local population. Land use change decisions in turn are affected by biophysical and socio-economic processes. In order to investigate the impacts and causes of land use change, numerous models have been developed. Moreover, these models can be used to project possible future land use changes (Alexander et al., 2016; Heistermann, 2006; van Asselen & Verburg, 2013; van Soesbergen, 2016).

For this report, the current and future location and extent of irrigated cropland areas is particularly crucial because irrigation agriculture is the world's largest water use sector (Döll, 2009; FAO, 2021a). In doing so, it competes with the energy-generating industry in water use and thus may affect the cooling water gap (see Table 4-4). The change in irrigated cropland areas is determined with LandSHIFT, a well-tested global land use change model that has been successfully applied for different global and regional studies (Alcamo et al., 2011; Göpel et al., 2020; Hinz et al., 2020; Koch et al., 2019). A full description of the modeling framework is given in (Schaldach et al., 2011) and (Schüngel et al., 2021). LandSHIFT is based on the concept of land use systems (Turner et al., 2007) and couples components representing the respective anthropogenic and environmental sub-systems. It operates on a global spatial grid with a cell size of 5 arc-minutes, which forms the micro level. Each grid cell is assigned to a country or region, which forms the macro level. During the simulation, LandSHIFT translates the macro level model drivers, such as population, number of livestock or crop production (12 different crop classes under rainfed as well as irrigated conditions), into spatial land use patterns. For historic simulation runs, macro level driver information is taken from statistics (e.g. FAOSTAT (FAO, 2021b)), while for future projections, it is taken from scenario assumptions. At the beginning of every five-year time step the preference of each raster cell for the different land use types is determined based on micro level information, such as land cover type, terrain slope or road infrastructure. Thereafter the model uses the macro level data to determine and allocate the land needed for each crop type, pasture and settlement to the most suitable grid cells. Main model results are raster maps depicting the spatial and temporal patterns of land use change. LandSHIFT determines the spatial distribution of land in three sub-modules, each representing a particular land use activity: settlement, crop cultivation, and livestock grazing. In addition, crop cultivation is split into an irrigated part, which is responsible for determining the spatial distribution of irrigated crop types, and a rainfed part, which subsequently determines the spatial distribution of rainfed crop types. As a result, two different crop types can exist on a grid cell, a rainfed crop type and an irrigated crop type, each with its own fraction of the grid cell area.

For a detailed description of the model input data, the determination of a cell's preference, and the algorithm for expanding irrigated cropland areas, see Appendix B.

4.2.2 Main drivers

In order to simulate changes in irrigated cropland areas up to 2040, we used scenario data on crop production, crop yields, and population. Since the global energy scenario studies (see Section 4.1.2) do not provide agricultural development information needed to simulate future land use change with LandSHIFT, we used results of the REMIND[1]-MAgPIE[2] integrated assessment modeling framework (Kriegler et al., 2017), which was used to quantify future global developments in the energy sector across different Shared Socio-Economic Pathways (SSPs) until 2100 (Bauer et al., 2017). In aggregated from, these datasets are freely available as part of the SSP database (Riahi et al., 2017). For the LandSHIFT simulations, we obtained the disaggregated agricultural data (crop class specific production and yields) through personal correspondence with the authors. The data were derived from results of two model runs, both for SSP2, with a global radiative forcing target of 2.6 (SSP2_26) as well as 4.5 (SSP2_45) W/m² by 2100. SSP2_45 is based on assumptions comparable to those of the reference scenario (IEA CP) (see Section 4.1.2), i.e. increasing primary energy demand, mainly from fossil fuels, up to 2040. SSP2_26 can be assigned to the decarbonization scenarios (see Section 4.1.2), with assumptions comparable to those of IEA SD or GECO B2°C, i.e. approximately constant primary energy demand up to 2040, but with decreasing use of fossil fuels and increasing use of bioenergy. The climate scenarios are described in more detail in Section 4.3.1.2.

Projections of population (total number, urban and rural shares) were taken directly from the country-level SSP database for SSP2 and account for both scenarios (KC & Lutz, 2017; Riahi et al., 2017). Since the results of REMIND-MAgPIE do not consider climate change, we used constant climate conditions for the potential crop yields on micro level. Moreover, REMIND-MAgPIE results do not provide information on the development of livestock units. Therefore, we kept the numbers constant for the whole simulation period. Development of agricultural production and yield is provided for 10 world regions (Figure 4-6) and distinguishes 17 crop classes, each under irrigated and rainfed conditions. Every country was assigned to a world region and the 17 crop classes were mapped to the 12 crop classes used by LandSHIFT (Table B 3 in Appendix B). Trends of crop production and yields were calculated for each crop class for all world regions in five 5-year time steps from 2020 to 2040, relative to the base year 2015. In detail, trends for crop production were applied to the coun-

---

[1]REMIND website: https://www.pik-potsdam.de/en/institute/departments/transformation-pathways/models/remind

[2]MAgPIE website: https://www.pik-potsdam.de/en/institute/departments/activities/land-use-modelling/magpie

try-specific statistical data from the Food and Agriculture Organization of the United Nations (FAO) and SPAM (see Section 4.2.1) of the base year while trends for crop yields were applied to the potential crop yields on grid cell level. Change in future population growth was calculated for each country individually based on the SSP2 scenario (KC & Lutz, 2017; Riahi et al., 2017).

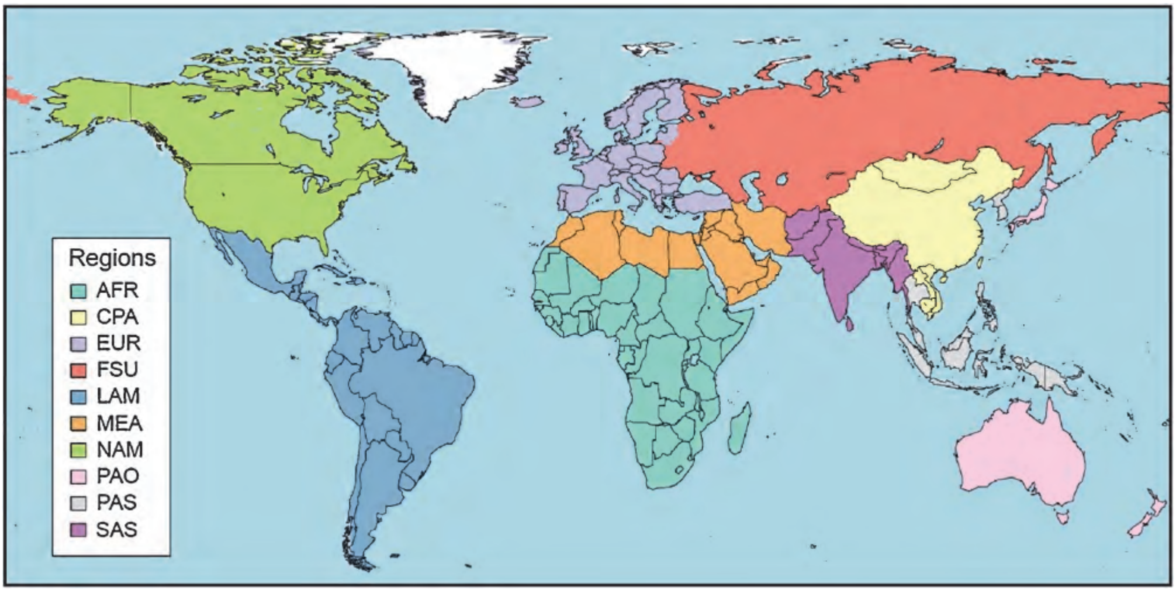

Figure 4-6: MAgPIE world regions. Sub-Sahara Africa (AFR), Centrally Planned Asia (CPA), Europe (incl. Turkey) (EUR), Former Soviet Union (FSU), Latin America (LAM), Middle East and North Africa (MEA), North America (NAM), Pacific OECD (PAO), Pacific Asia (PAS), South Asia (SAS) Schmitz et al., 2012).

Table B 4– Table B 7 in Appendix B show in detail the trends of production and yields for every world region, irrigated crop class, time step and scenario. Figure 4-7 depicts the summarized irrigated production volumes of the world regions for the base year 2015 (combined data from FAO and SPAM) as well as the resulting crop production volumes for 2030 and 2040 according to the trends of the scenario assumptions. Figure 4-8 presents the summarized global production volumes of each irrigated crop class also for the base year 2015 as well as the resulting production volumes for the years 2030 and 2040. Global production of crops under irrigated conditions increases from approximately 2,900 million tons in 2015 to about 4,850 (SSP2_45) and 5,200 million tons (SSP2_26) in 2040, mainly driven by the regions CPA and LAM, which already show high values in 2015 and an increase of 88% (CPA, SSP2_45) and 138% (LAM, SSP2_26) by 2040, respectively. The AFR region is characterized by low irrigated crop production in the base year, but increases its production by about 450% by 2040. On global scale, tropical cereals show by far the highest increase in both scenarios, especially in the LAM region, but remain of secondary importance in terms of absolute numbers. The crop classes rice, maize, sugarcane, temperate cereals, and other crops, which are already produced in larger quantities in 2015, will mainly be responsible for the global increase, with growth rates between 40% and 166% by 2040.

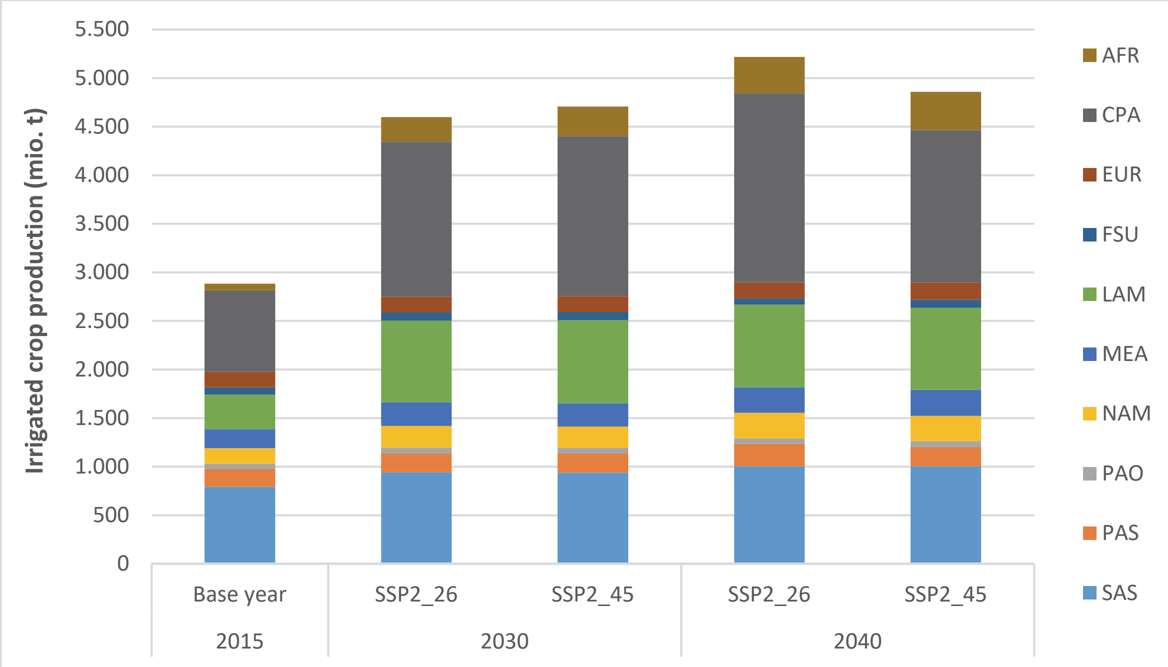

Figure 4-7: Summarized scenario input data for irrigated crop production for the 10 world regions

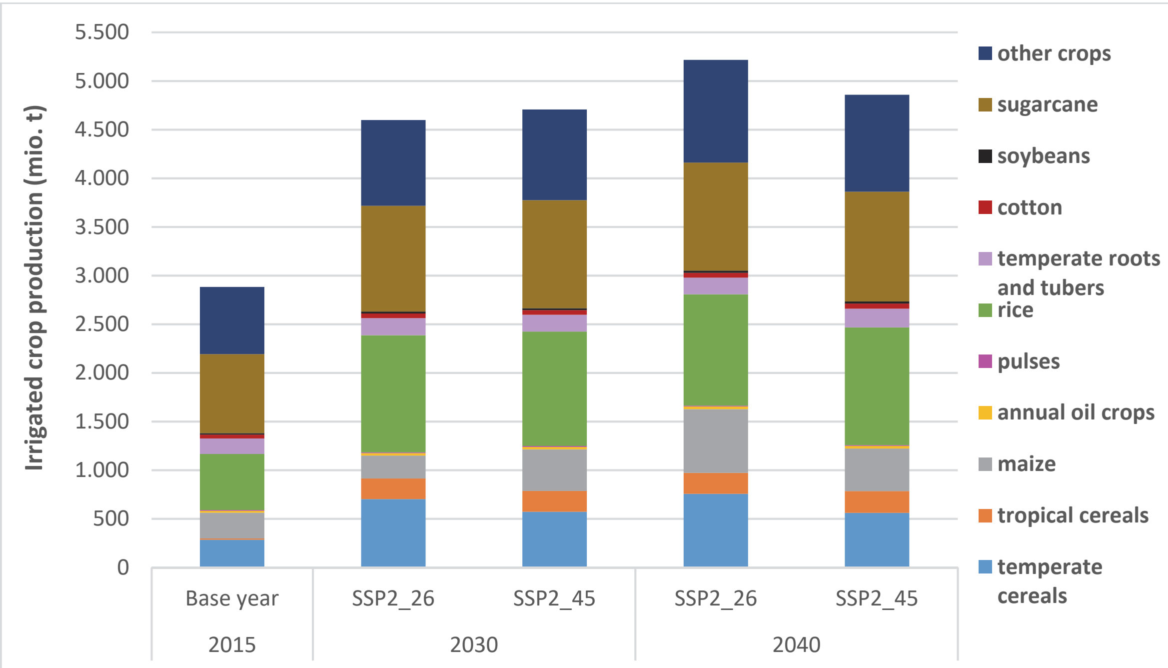

Figure 4-8: Summarized scenario input data for global irrigated crop production for every irrigated crop class

4.2.3 Key results

Main outcomes of the LandSHIFT model are global raster maps depicting the spatial patterns of land use change for each predefined time step. For this report, we focus on the change in irrigated cropland areas since irrigation agriculture is a competitor to the energy-generating industry in terms of water use and thus may affect the cooling water gap (see Section 4.4.1).

Figure 4-9 visualizes the irrigated fraction per grid cell with a spatial resolution of 5 arc-minutes for the base year 2015 as well as for the scenario year 2040. Figure 4-10 shows the summarized irrigated areas of the different world regions for the year 2015 as well as for the scenario years 2030 and 2040. The world regions EUR, FSU, MEA, PAO, PAS and SAS show only little changes in irrigated area in both scenarios by 2040. The moderate increases in production volumes are compensated by increasing yields. In the NAM region, irrigated area increases by about 20% (SSP2_26) and 25% (SSP2_45) by 2040, mainly as a result of intensification, i.e., expansion on grid cells that already have an irrigated fraction larger than zero, such as in the California Central Valley. In the CPA region (strongly dominated by China), irrigated areas increase by 68% for the SSP2_45 scenario and nearly double for the SSP2_26 scenario by 2040 compared to the base year, and is thus the main driver of the global increase in irrigated areas. While the irrigated land expansion is driven by intensification in the eastern part of China, the expansion in northern and western China is caused by new equipment of land area that was not yet irrigated. By far the highest increase in irrigated areas occurs in the regions AFR and LAM, which roughly quintuple their areas in both scenarios. In the LAM region, most of the expansion is taking place in Mexico, which is massively affected by the vast increase in production of irrigated tropical cereals, because large amounts of these crops are already produced in the base year 2015. The resulting expansion takes place where irrigated area already exists as well as on new additional area equipped for irrigation like in the northern part of the country. Also, in Argentina, irrigated areas are expected to increase significantly, mainly caused by the vast increase in the production of irrigated tropical cereals. While in the northern part of Argentina expansion occurs through an intensification of agricultural practices, in the southern part, especially alongside the Río Negro, expansion of the irrigation area takes place mainly on newly equipped areas. In the AFR region, expansion affects eastern Africa as well as South Africa and Nigeria. Because irrigated area is small in these regions in the base year 2015, the expansion results in new land to be equipped for irrigation in order to fulfill the strong increase in production.

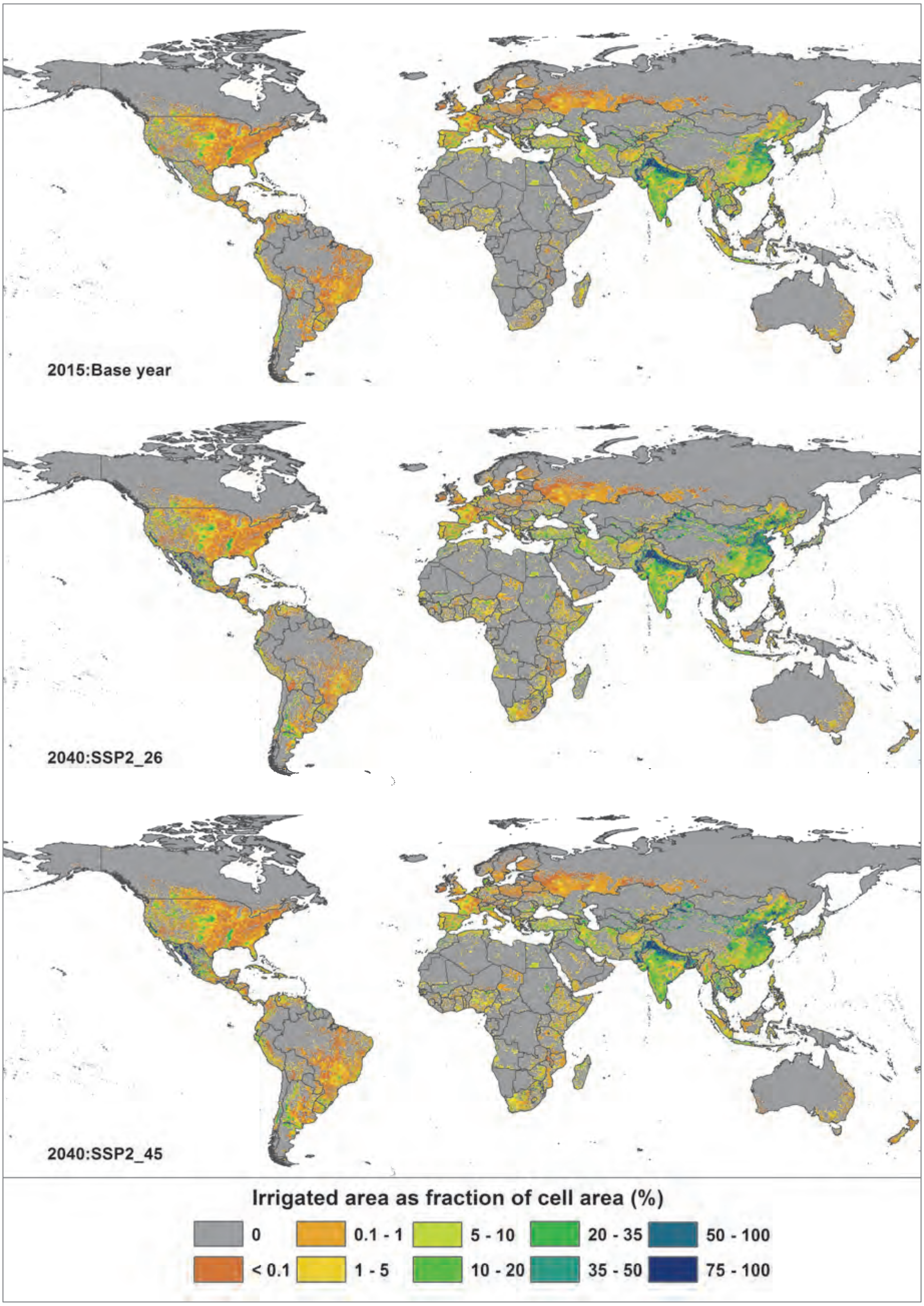

Figure 4-9: LandSHIFT simulation results of irrigated fractions per grid cell. Spatial resolution: 5 arcminutes.

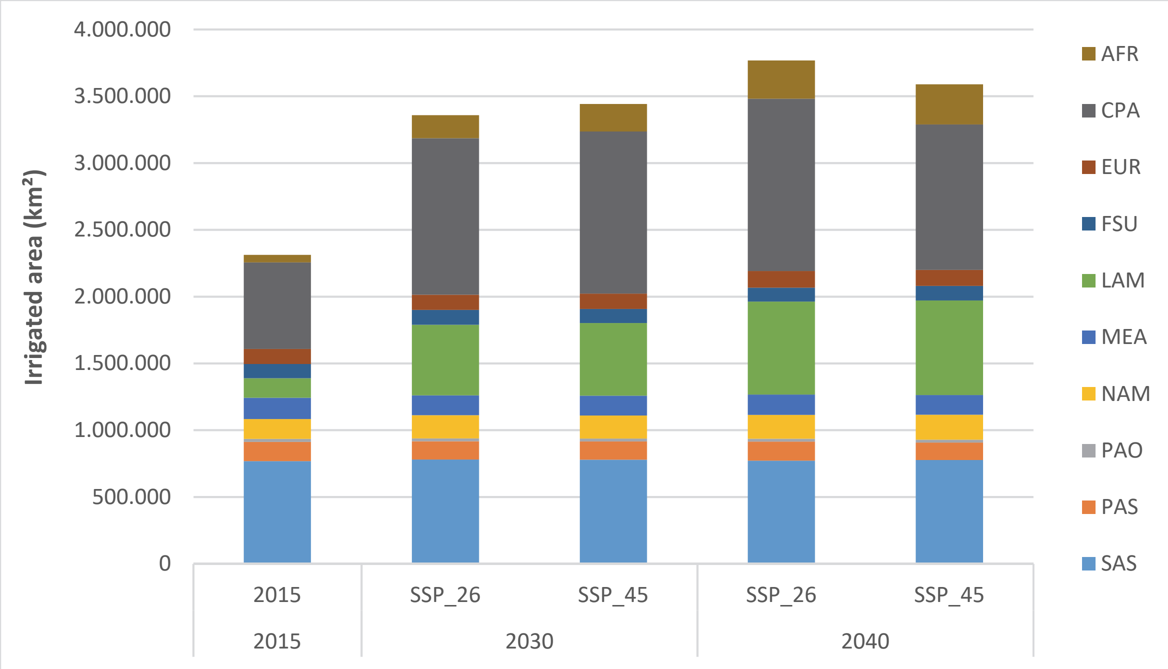

Figure 4-10: Summarized LandSHIFT simulation results of irrigated areas for the 10 world regions

4.3 Water Resources

4.3.1 Future water availability

Authors: Martina Flörke, Ellen Kynast, Jenny Kupzig

We used the integrated global water modelling framework WaterGAP3 to simulate current and future water availability and sectoral water uses globally over the entire timeseries from 1981 to 2060. For all analyses, we considered the model results representing the baseline period (time period from 1981 to 2016) and future period (referred to as the 2040s, the time period 2031–2060). The components of the modelling framework, main input data and data analysis are briefly described in the following sections.

4.3.1.1 Modelling approach

The global hydrological model WaterGAP3 simulates the characteristic macroscale behaviour of the terrestrial water cycle in order to estimate the renewable freshwater availability on a 5 × 5-arcmin spatial resolution, i.e. about 9 by 9 km at the equator (Eisner et al., 2017; Schneider et al., 2011; Verzano et al., 2012). Based on the time series of climatic data, the hydrological model calculates the daily water balance for each grid cell, considering physiographic characteristics such as soil type, vegetation, slope, aquifer type, permafrost and glaciers. The runoff is generated on the grid cells and routed to the river basin outlet on the basis of a global drainage direction map obtained from the HydroSHEDS database (Lehner et al., 2008). The hydrological influence of lakes, managed reservoirs and dams as well as wetlands is considered in the lateral routing process. Location and extent of surface water bodies are derived from the Global Lakes and Wetlands Database (GLWD, Lehner and Döll; 2004) and mapped to the river basin set. Further, a total number of 6,025 reservoirs and dams are implemented in the model by their location and other information as provided by the Grand Reservoir and Dam Database (GRanD; Lehner et al., 2011). The operation of dams depends on the dam type and relates to the main purpose given in GRanD. In WaterGAP3, the management of irrigation, hydropower, water supply, navigation and flood protection dams is differentiated (Schneider et al., 2017). In a standard model run, river discharge is simulated in approximately 2.2 million grid cells globally.

Simulated river discharge is calibrated against observed mean annual discharge data from the Global Runoff Data Centre (GRDC, 2004) at about 2,446 stations globally, except Antarctica and Greenland, covering about 51% of the global land area. The selection of stations has to fulfill three main criteria: (1) an upstream area of at least 3,000 km^2; (2) a timeseries of at least five (complete) years; and (3) an inter-station catchment area to the next upstream station of at least 5,000 km^2. During the calibration process one free parameter (i.e., runoff coefficient γ) is adjusted to all grid cells within a river basin in order to ensure that the simulated long-term average discharge is within 1% of the observed one (Eisner 2016). The runoff coefficient is allowed to vary between 0.1 and 5. In river basins where the deviation between simulated and observed river discharge remains larger than ±1% a runoff correction factor is assigned to each cell within the basin (same value for each cell). The calibrated runoff coefficients are transferred to ungauged basins using a multiple linear regression approach that relates the calibrated values of the runoff coefficients to several basin descriptors.

Five meteorological variables are required to force WaterGAP3: air temperature, long-wave downwards surface radiation flux, short-wave downwards surface radiation flux, rainfall rate and snowfall rate.

4.3.1.2 Main drivers

The global scale hydrology model WaterGAP3 was forced by the EWEMBI meteorological data compiled to support the bias correction of climate input data for the impact assessments carried-out for ISIMIP2b (i.e., phase 2b of the Inter-Sectoral Impacts Intercomparison Project; Frieler et al., 2017). The EWEMBI data cover the entire globe at 0.5° horizontal (50 x 50 km at the equator) and daily temporal resolution from 1979 to 2016 (Lange, 2019). In order to obtain the best possible fit with the energy (cf. section 4.1) and land use change (cf. section 4.2) scenarios, time series of bias-adjusted climate projections from four GCMs were selected from the ISIMIP2b database. These four GCMs were GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, and MIROC5 (see Table 4-2) and based on a radiative forcing of 2.6 W/m^2 (RCP2.6) and 4.5 W/m^2 (RCP4.5), respectively.

Table 4-2: Global Climate Models (GCMs) and scenarios (Representative Concentration Pathways, RCPs) used in this study

GCM	RCP	Modelling Period	Organization
GFDL-ESM2M	2.6, 4.5	Baseline: 1976-2005 Scenarios: 2031-2060	National Oceanic Atmospheric Administration, Geophysical Fluid Dynamics Laboratory, Princeton, USA
HadGEM2-ES			Met Office Hadley Centre, Exeter, UK
IPSL-CM5A-LR			Institute Pierre-Simon Laplace, Paris, France
MIROC5			Center for Climate System Research, The University of Tokyo, Kashiwa, Japan

The radiative forcing estimates are based on the forcing of greenhouse gases and other forcing agents, and the forcing levels are relative to pre-industrial values (Moss et al. 2010, Van Vuuren et al. 2011). The selected RCPs include one mitigation scenario leading to a very low forcing level (RCP 2.6) and a medium stabilization scenario (RCP 4.5). RCP 2.6 has the radiative forcing trajectory of first going to a peak forcing level of 3.1 W/m^2 followed by a decline, and aims to limit the increase of global mean temperature to less than 2 °C by 2100. For HadGEM2-ES and IPSL-CM5A-LR, global mean temperature (GMT) returns to warming levels below 2 °C after 2100. RCP 4.5 is a stabilization scenario in which total radiative forcing is stabilized before 2100 by employment of technologies and strategies for reducing greenhouse gas emissions. Each GCM reaches different global warming levels at different times (Table 4-3), depending on the RCPs. By definition, the time of exceeding a global warming level is reached when the 31-year running mean of the global averaged annual mean temperature passes this level for the first time.

GCM selection was primarily based on availability of daily output of a list of atmospheric variables for different RCPs as required by the broad variety of (impacts) models participating in ISIMIP (Frieler et al., 2017; Hempel et al., 2013). The selected models cover a broad response space defined by global temperature and the ratio of land-averaged precipitation increase per GMT at the end of the 21st century. As GCM output differs significantly from observations, GCM output was bias-adjusted before being used as input to the impact models. The bias adjustment method used for the GCMs in ISIMIP2b is using a trend preserving algorithm (Frieler et al., 2017; ISIMIP, 2018) with EWEMBI (Lange, 2018) as target.

The EWEMBI and GCM meteorological forcing cover the entire globe at 0.5° x 0.5° spatial resolution and were simply downscaled to the 5 arcmin spatial resolution as required by the WaterGAP3 model.

Table 4-3: Year in which the (bias-corrected) 31-year running mean of global mean temperature crosses the given thresholds.

Warming Level	RCP	GFDL-ESM2M	HadGEM2-ES	IPSL-CM5A-LR	MIROC5
1°	2.6	2014	2012	1993	2015
	4.5	2014	2015	1993	2017
1.5°	2.6	-	2026	2009	2048
	4.5	2049	2031	2011	2039
2°	2.6	-	-	2029	-
	4.5	-	2046	2029	2069
3°	2.6	-	-	-	-
	4.5	-	-	2066	-

4.3.1.3 Key results

The spatial distribution of the ensemble of GCM-derived long-term average annual water availability according to sub-basins for the baseline period 1976-2005 is shown in Figure 4-11. Model results are rather similar to simulation results obtained with different data sets of observed climate and different model versions (not shown). However, this map sharpens the contrast between adjacent water-rich and water-poor areas. Furthermore, simulated future changes in water availability are related to the baseline conditions as realized by the individual GCMs input.

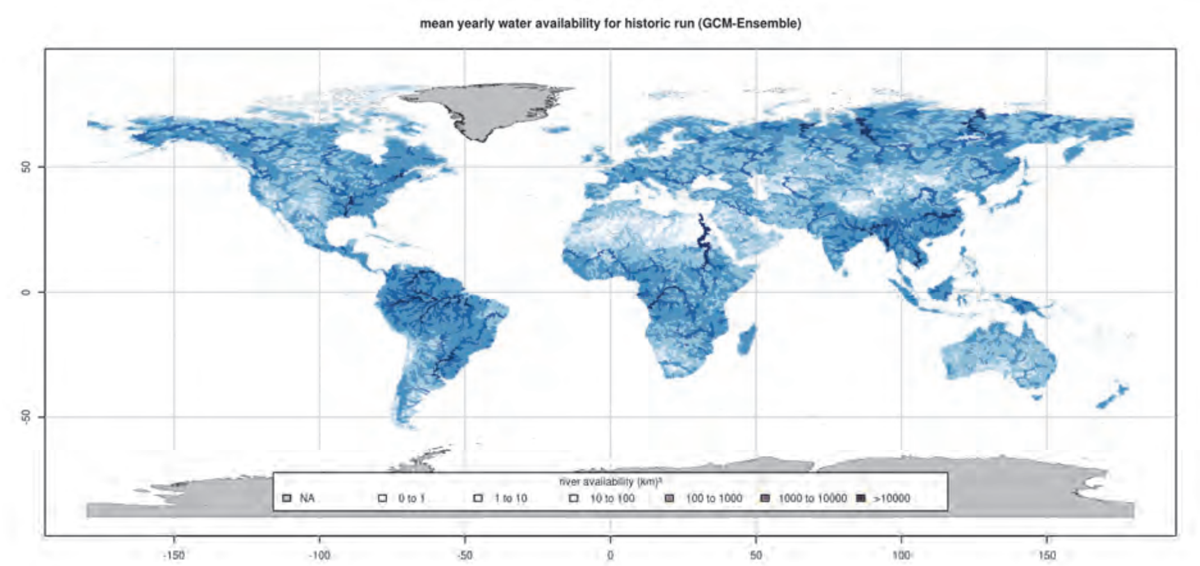

Figure 4-11: Long-term average annual renewable water availability calculated as ensemble mean for the baseline climate

In the future, an expected increase in air temperature intensifies evapotranspiration, and hence reduces runoff, while changes in precipitation will raise or lower the average volume of river discharge. These two effects interact differently at different locations and produce the net increase or decrease in long-term annual water availability as shown in Figure 4-12 to Figure 4-15. An ensemble of climate input from four GCMs and two RCPs was selected to consider the uncertainty not only caused by modeling physical processes but also to address the consequences of modeling decisions that lead to different results. The model results of the future projections (i.e., 2040s) are expressed as relative changes to the GCM-baseline. Here, it should be noted that changes of zero or close to zero numbers lead to infinite decreases or increases in water availability, such as in the desert areas. The model results for the individual GCMs are presented below.

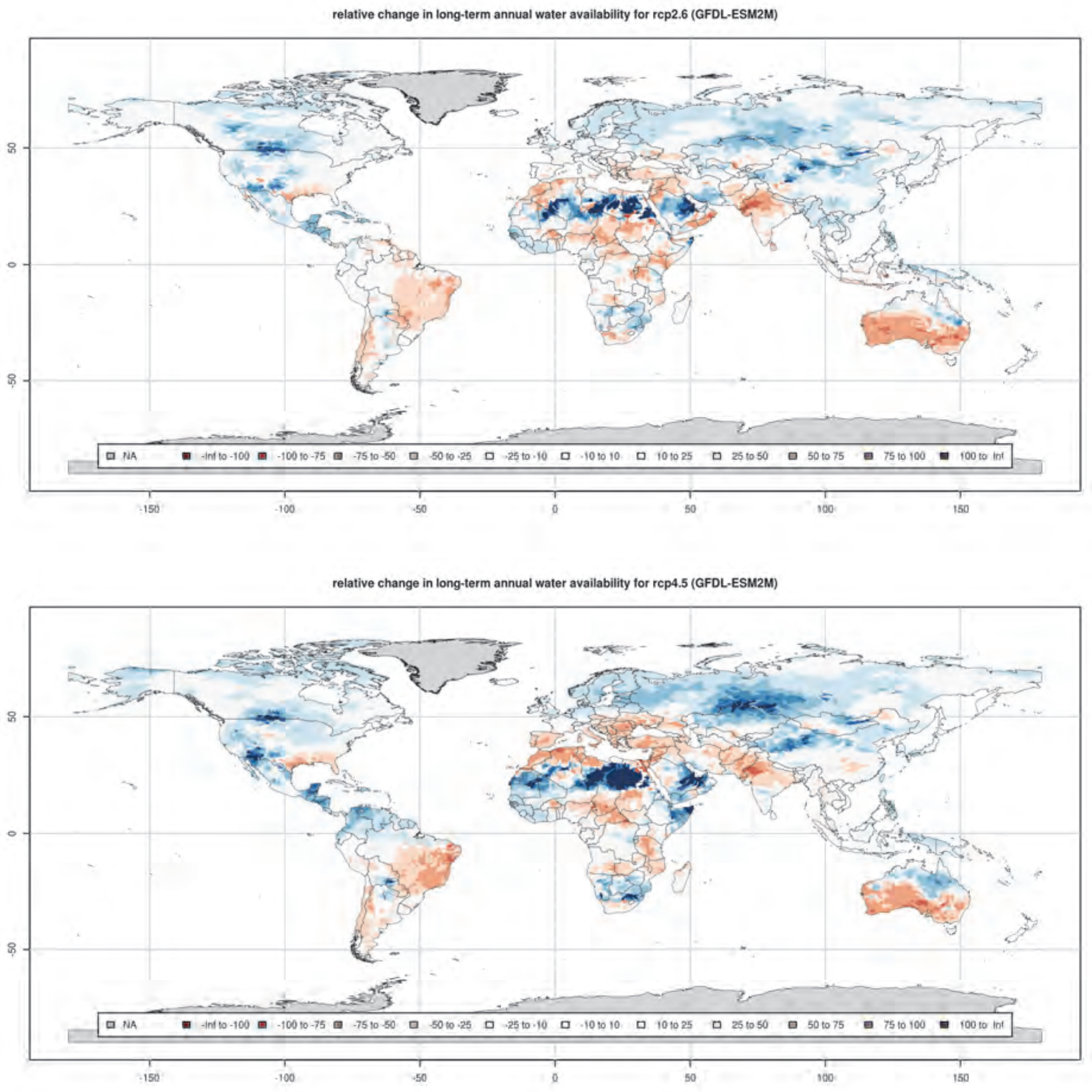

Figure 4-12: Relative change in annual discharge on a river basin scale in 2040s compared to baseline conditions, under RCP2.6 (top) and RCP4.5 (bottom) for GFDL-ESM2M

To assess the impact of climate change on annual water availability Figure 4-12 shows the changes between the baseline conditions and a world under a RCP2.6 (Figure 4-12 top) and RCP4.5 (Figure 4-12 bottom) scenario for the 2040s as realized with the GFDL-ESM2M climate input. Although the GMT remains well below 1.5 °C in the RCP2.6 projection (cf. Table 4-3), the model outcomes show decreases in annual water availability of more than 25% in 2040s in South America and in the Mississippi Basin as well as countries of the Mashriq, sub-Saharan Africa and South Asia. Mediterranean rim countries and the Black Sea region are likely to be negatively affected by climate change, too, but these effects become stronger under RCP4.5. However, a decrease in annual water availability of more than 50% is expected for south Australia while the northern part of the country will likely face an increase. Increases in annual water availability of more than 25% become also visible in several regions of the world such as China, Central Asia, Russia, Northern Europe, North and Central America, and northern parts of South America.

Model results obtained with the RCP4.5-driven climate input displays the same but more pronounced pattern of increasing and decreasing changes in renewable water resources in the future (2040s).

Figure 4-13 depicts the change in annual water availability between the RCP2.6 (Figure 4-13 top) and RCP4.5 (Figure 4-13 bottom) scenarios for the 2040s and the baseline period (1976-2005). The climate input is derived from the GCM of the Hadley Centre (HadGEM2-ES). GMT stays below 2°C in the RCP2.6 projection of the HadGEM2-ES model but exceeds 1.5°C in 2026, whereas the RCP4.5 projection reaches 2°C in 2046 (Table 4-3). Overall, patterns of increasing and decreasing trends in long-term annual water availability differ from those simulated with GFDL-ESM2M climate input. Negative relative changes of more than 25% are computed for areas in North America, Brazil, Northern Africa, Arabian Peninsula, and Western Australia. Relatively small changes in annual water availability are computed for most of Europe's river basins for both RCPs up to the 2040s. Conversely, nearly all of Scandinavia, Northern Russia, China, and India display an increase in annual water availability up to 50% caused by a changing trend in future precipitation.

In contrast to the model results driven by GFDL-ESM2M climate input, not all patterns of change are intensified under the RCP4.5 scenario, some trends become weaker or even reverse (e.g., USA, Southern Africa).

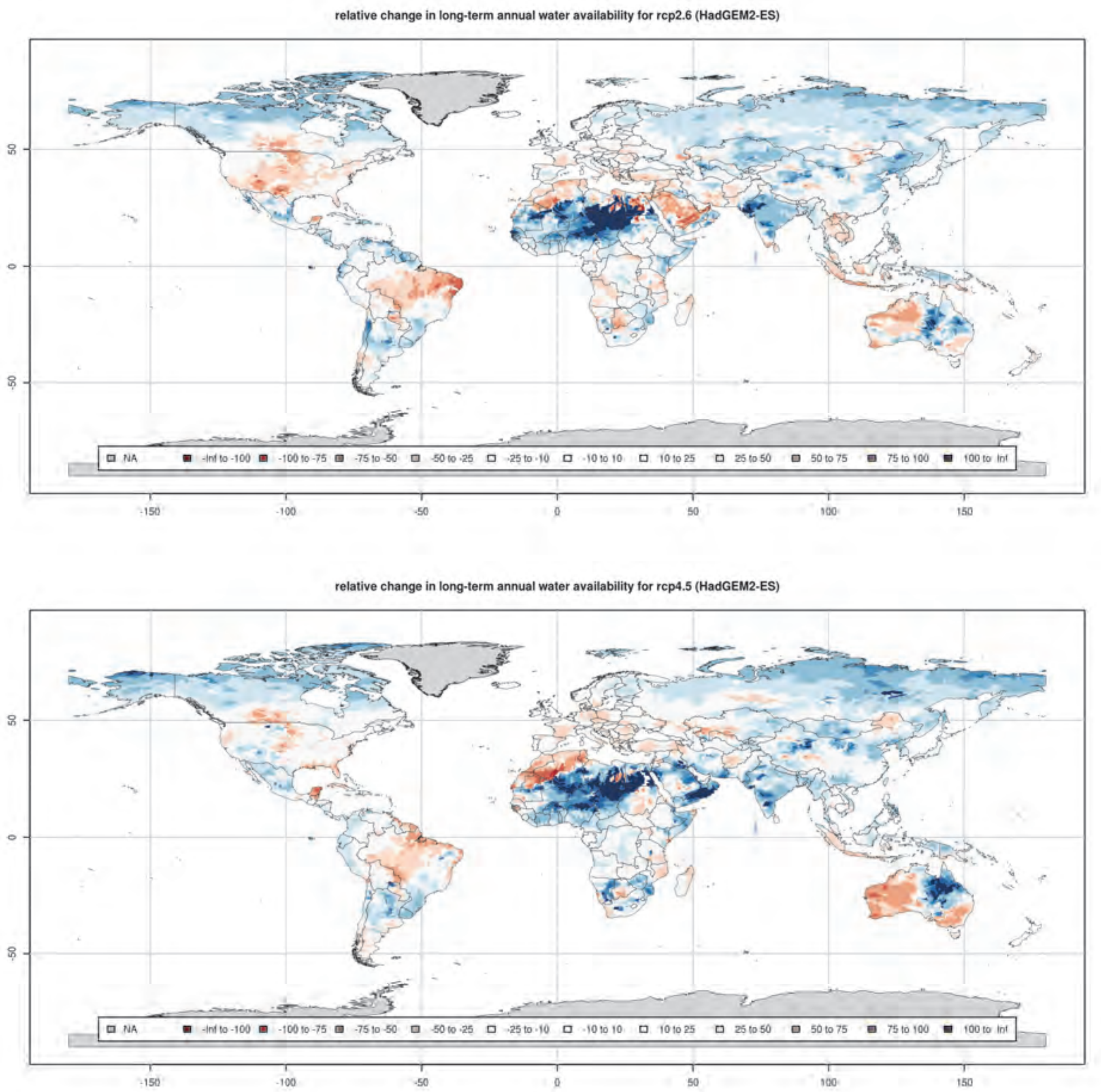

Figure 4-13: Relative change in annual discharge on a river basin scale in 2040s compared to baseline conditions, under RCP2.6 (top) and RCP4.5 (bottom) for HadGEM2-ES

The maps presented in Figure 4-14 give an overview of changes in average annual water availability between the 2040s and the baseline as simulated by WaterGAP3 based on the RCP2.6 and RCP4.5 climate projections of the GCM IPSL-CM5A-LR. GMT increases are expected to exceed 2°C with both projections in 2029 and even 2.5°C are passed by RCP4.5 within our time frame of interest (i.e., in 2044, Table 4-3). Compared to the other GCMs, the changes in water availability reflect the climate input (especially precipitation) of this GCM. Decreasing trends in annual water availability of up to 50% are already expected for Central America, Northern Africa, Central and South Asia (except India), and even up to 75% in Australia under the RCP2.6 scenario. As for the HadGEM2-ES results, small changes in annual water availability are calculated for the Mediterranean rim countries, except for Spain and North African countries which are affected significantly (up to -75% in the

RCP4.5 scenario). A reduction of up to 25% is likely to occur in the future in northern and southern parts of South America, Western sub-Saharan Africa, and eastern China. In general, long-term annual water availability is expected to increase in Northern and Western America, Brazil, Northern Europe, Russia, and East Africa.

Similar to the GFDL-ESM2M-driven results, increasing and decreasing changes are in general more pronounced in the RCP4.5 scenario compared to RCP2.6.

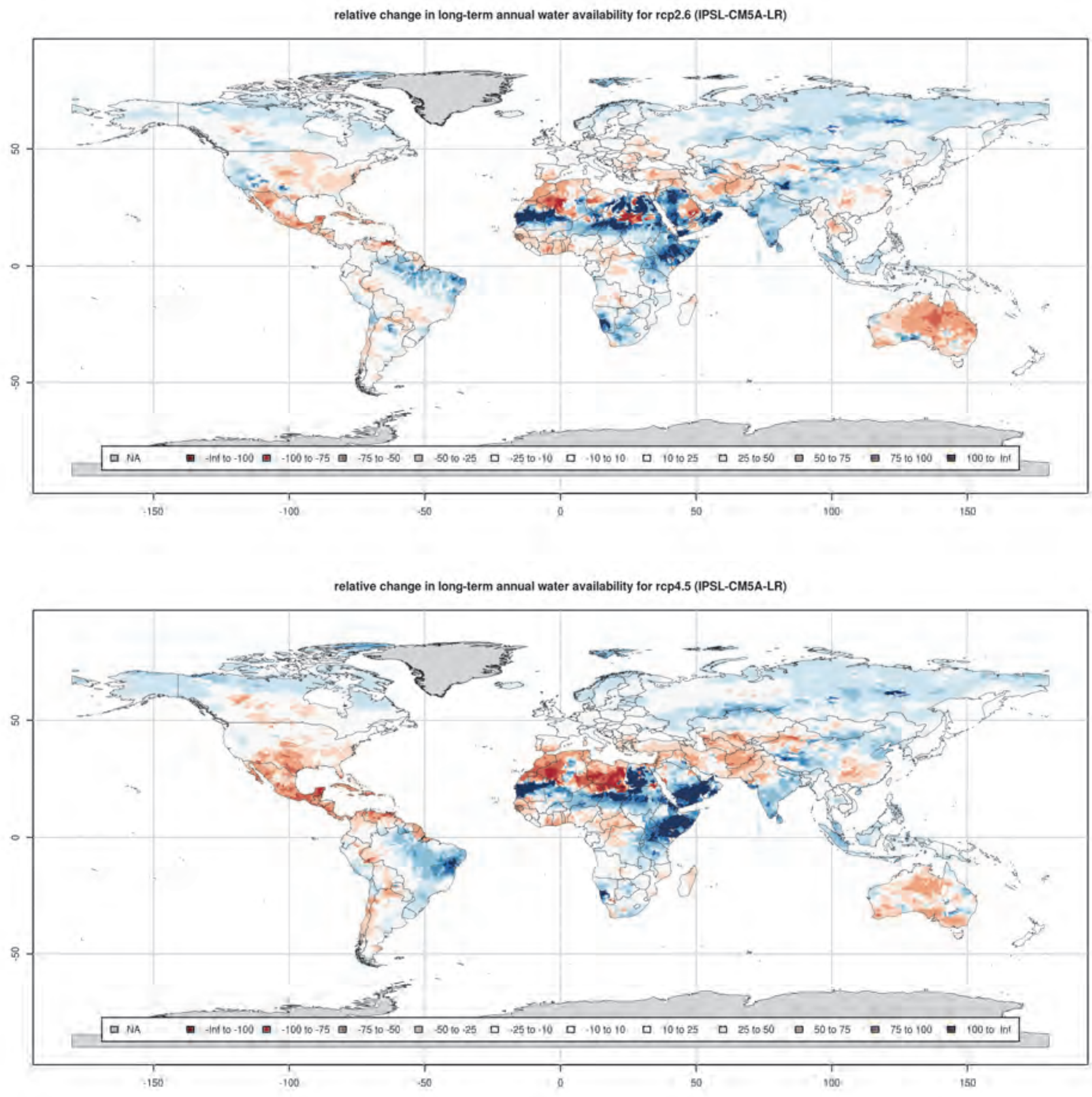

Figure 4-14: Relative change in annual discharge on a river basin scale in 2040s compared to baseline conditions, under RCP2.6 (top) and RCP4.5 (bottom) for IPSL-CM5A-LR

Relative changes in annual water availability between the 2040s and the baseline conditions as simulated with the MIROC5 climate projections again lead to different patterns compared to the results described above (Figure 4-15). However, GMT increases slower than HadGEM2-ES and IPSL-CM5A-LR and likely exceeds 1.5°C in 2048 (RCP2.6) whereas the RCP4.5 projection passes 1.5°C in 2039 and 2°C in 2069, respectively (Table 4-3). While some similarities exist to the other GCMs, differences occur for Eastern Europe and large parts of Russia which are indicated by a decrease in water availability of up to 25% in the RCP2.6 scenario which is less severe in the RCP4.5 scenario. In the RCP2.6 scenario, most patterns of decreasing trends in water availability are between 10 and 25% with few local exceptions. On the opposite, increasing water availability is computed for northern America, eastern Russia, South Asia, North West Pacific and East Asia, central South America, and large parts of Africa.

As for the model results based on the HadGEM2-ES projections, MIROC5 leads to results where patterns of change are intensified under the RCP4.5 scenario (compared to RCP2.6), but also become weaker or shift.

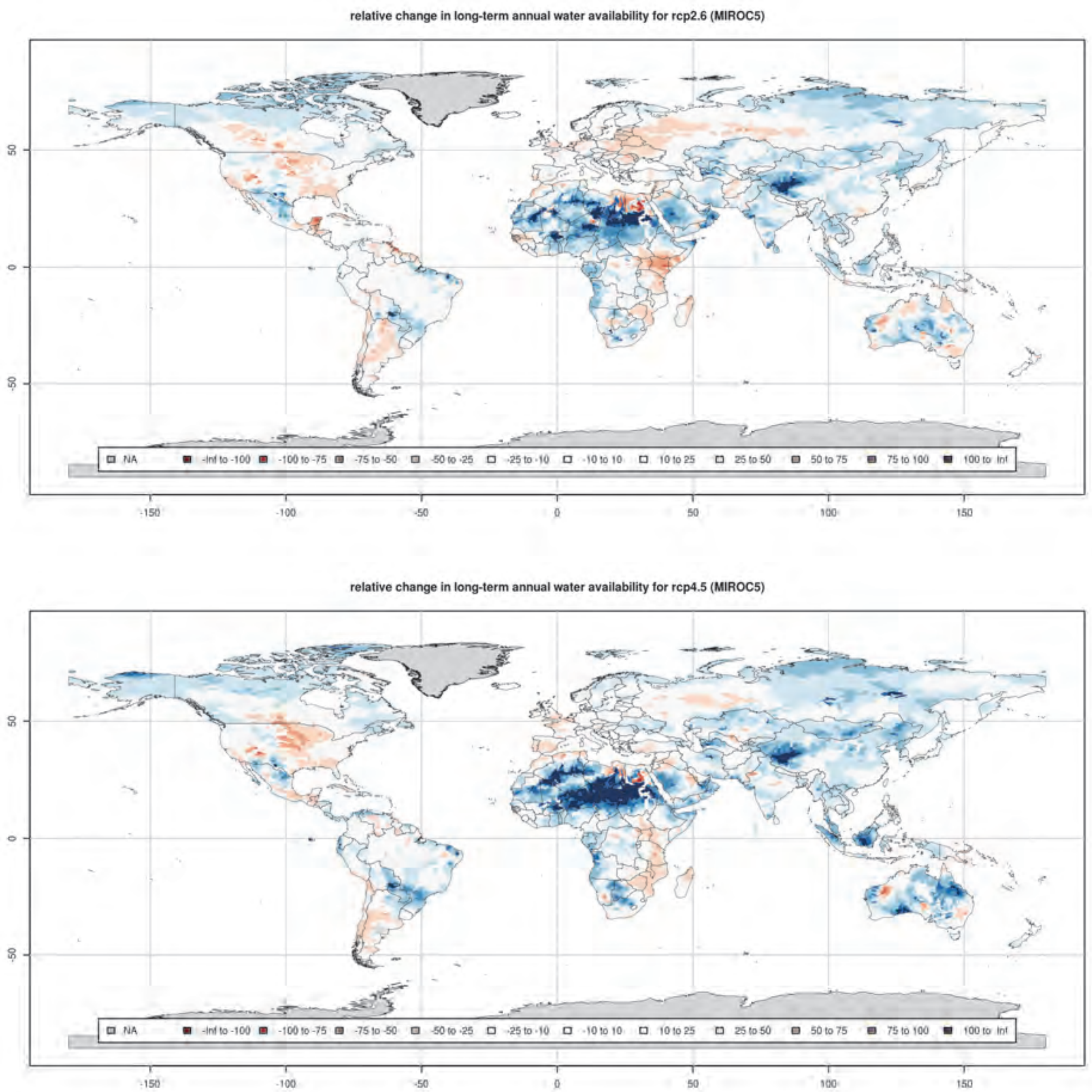

Figure 4-15: Relative change in annual discharge on a river basin scale in 2040s compared to baseline conditions, under RCP2.6 (top) and RCP4.5 (bottom) for MIROC5

In conclusion, computed changes in annual water availability vary strongly among GCMs in several parts of the world, and hence, are subject to uncertainties. For example, in some regions (USA, Brazil, India), forcing by the different GCMs yields discharge changes that can be large but of opposite sign. Accordingly, the spread due to differences between GCMs dominates the total ensemble spread in these regions. The bias–correction applied to the GCM data substantially reduces the spread among the GCMs' present–day climatologies, but not among their future climate trends (Hempel et al. 2013).

4.3.2 Future water use

Contributing Authors: Martina Flörke, Ellen Kynast, Jenny Kupzig, Christopher Jung

Water demand has been increasing and continues to increase globally, as the world population grows and nations become wealthier and consume more. As water demands get closer and closer to the renewable freshwater resource availability, each drop of freshwater becomes increasingly valuable and water must be managed more efficiently and intensively. Planning for future development and investments requires that we prepare water projections for the future. However, estimations are complicated because the future of World's waters will be influenced by a combination of important environmental, social, economic and political factors, such as global climate change, population growth, land use change, globalization and economic development, technological innovations, political stability and international cooperation. Climate change and the other factors external to water management are demonstrating accelerating trends or disruptions. In this section we provide results of the two water use sectors that are interlinked to electricity production: thermoelectric power plants (water used for cooling and cleaning of solar panels) and agriculture (water used for irrigation). Sometimes the water evaporated in reservoirs of hydroelectric power stations are reckoned as water requirements of electricity production, but we do not take this into account in our study. Even though the agricultural sector is the main water consuming sector, in some regions, for example, USA and Europe, more than 40% of the total water withdrawals are used for cooling purposes to produce thermal electricity.

4.3.2.1 Modelling approach

This section describes the modelling approach of the WaterGAP3 sub-modules used to calculate the water demand of the domestic, manufacturing, electricity production, and agricultural sectors. Because we focused on electricity generation and agricultural water uses, these two modelling approaches are described in more detail.

<u>Water demand for electricity production:</u> The WaterGAP3 sub-module is used to calculate water demand of thermoelectric power plants for the reference year (2015) and different future scenarios in 2040. For the future conditions, one reference scenario and three decarbonization scenarios are selected which differ in Greenhouse Gas Emission Changes (compared to 1990) and share of renewable energy sources contributing to the future energy mix of. Details on the scenario selection process, the description of the different future energy

pathways as well as estimates of global and regional water withdrawals and water consumption are explained in Section 4.1.

The objective of the sub-model is to compute freshwater withdrawals and consumption for the production of electricity location-specific per power plant. Input data on location, type and size of power stations are based on the World Electric Power Plants Data (Utility Data Institute, 2004, updated in 2010) and extended by literature and case study information, which results in a total number of 48,522 power plants considered of which 32,152 were active in 2015. Power plants that use seawater or brackish water for cooling purposes are not taken into consideration. In this context, a thermoelectric power plant is a power-generating plant which uses heat to produce energy. Such plants may burn fossil fuels, biomass or use nuclear energy to produce the necessary thermal energy. In addition, we included geothermal power plants and Concentrated Solar Power (CSP) plants as well as other solar-related power plants to the database which need water for cooling (geothermal, CSP) and cleaning of the solar panels.

The amount of water withdrawn by each power plant using freshwater for cooling and cleaning is computed by multiplying the annual electricity production [MWh/year] with the water use intensity of the power station, i.e. the water abstracted per unit electricity production (in m^3/MWh). Data on annual electricity production is described in the next section 4.3.2.2. The total water withdrawn needed for cooling of power plants depends mainly on cooling system type, source of fuel (efficiency) and installed capacity. Different types of fuels (biomass, waste, nuclear, natural gas, oil, coal, petroleum) and energy sources (geothermal, CSP, PV) are distinguished and characterized by their respective water use intensities (Flörke et al., 2013; Terrapon-Pfaff, 2020). In regards to cooling systems, recirculation systems (e.g., tower cooling), once-through systems, and ponds are differentiated (Flörke et al.,2012). In general, once-through systems withdrawn relatively large quantities of surface water, and subsequently discharge high heat loads to the same water body after leaving the condenser. Recirculation systems use cooling towers to cool the water via con-tact with air before the water is discharged back to the surface water body. These systems require smaller amounts of surface water withdrawal, but water consumption is higher (due to evaporative losses) compared to once-through systems (Koch and Vögele, 2009).

The total annual thermal power plant water withdrawal (TPWW) in each grid cell is then calculated as the sum of water abstracted by all power plants located in the same cell (Vassolo and Döll, 2004; Flörke et al., 2013). The allocation of the power plants to the global grid of the model is carried out by the geographical coordinates that could be assigned to the power plants. For future simulations, no new locations are identified for the construction of new power plants, instead capacities are expanded at current locations.

Further developments of the model: The available data of the selected energy scenarios (see Section 4.1) were available on a regional basis and had to be disaggregated to country level. Due to the focus on energy sources the disaggregation of regional electricity production numbers (e.g. for Africa, Latin America) could not be carried-out on the basis of the total production in regard to the reference year 2015 (or following historical trends). Instead, it was performed fuel-specific and a new approach was developed for the distribution of regional numbers to country values. For the distribution of regional values, a factor was first calculated for each country/fuel combination, which determines the share of the country value and fuel in the region. However, if there are regions where fuels will be used in the future that are not found in the reference year, a rule is needed to distribute the regional values to the respective countries. In the case of biomass, it is assumed that all countries will use biomass for electricity generation in the future (if given in a scenario for the whole region) at locations of power plants that burned biomass, gas, oil or coal in the past. Here, another factor is determined to allocate regional scenario values (equally) among all countries in a region. For power plants that are marked as “under construction” in the database, these will be connected to the grid in 2020, while the power plants marked as “planned” are connected to the grid in the first year of the land/fuel occurrence in the, but at the latest in 2030. Further, in some cases it was possible to find out locations of planned power plants, e.g. locations for future nuclear power plants in Australia, Bolivia, Paraguay, Malaysia and Thailand, as well as CSP power plants in Cape Verde and Mayotte. To account for CSP and solar power plants, the water use model was extended to include water use intensities for the calculation of water abstractions and consumption. In addition, the dates for phasing out coal-fired power generation in various countries were recorded by means of literature research and considered in the model simulations.

Water demand for irrigation: The WaterGAP3 sub-module is used to calculate water withdrawals and water consumption for irrigation purposes of field crops and rice for the baseline conditions and future scenarios on a grid cell level (5 by 5 arcminutes geographical resolution). The modelling approach is based on the approach of Allen et al. (1998). Here, the optimum supply of water to irrigated plants is simulated taking into consideration the climatic conditions and a field-crop-specific evapotranspiration coefficient (Kc). The Kc value represents the different evapotranspiration behavior of different crops on the one hand, and on the other hand the specific water demand with respect to the different phenological stages of the growing season(s). A distinction is made between the initial stage, the growing and fruiting phase and the late stage.

In the model, the spatial distribution of the crops is calculated in the first step (see Section 4.2), i.e. the irrigated areas of the individual crops are calculated for each grid cell of the first two growing seasons. Subsequently, the optimal growing period is determined depending on the climate conditions. The net irrigation requirement (i.e., water consumption) within the growing period is then calculated from the difference between the calculated water requirement and the available water quantity from precipitation and soil water. In addition to the net irrigation requirement of the crop, the calculation of the total irrigation requirement includes the irrigation efficiency, which considers factors such as management, distribution losses, field size and technology used and typically ranges from 0.3 to 0.8 depending on a type of irrigation (e.g., drip, sprinkler, surface irrigation) (Rohwer et al., 2007; Rost et al., 2008). For a detailed description of the irrigation module see Döll and Siebert (2002) and aus der Beek et al. (2010).

4.3.2.2 Main drivers

Cooling water sub-model: The amount of freshwater used for cooling in thermal power plants is mainly affected by the amount of electricity generated by these plants. The projections for future electricity production in Figure 4-2 show the trends of pathways until 2040 indicating the energy mix of the reference scenario (i.e., IEA CP) and three decarbonization scenarios (i.e., IEA SD, GP Adv. [R], GECO B2°C). In the future, electricity production is expected to increase between 50% and 100% up to 2040 globally. However, the share of renewable energy sources contributing to the energy mix is expected to increase in all of the scenarios (Table 4-1), but only two scenarios show a positive effect on water savings without further improvements in technology (IEA SD and GP Adv. [R], Figure 4-3). Improvements in energy efficiency or new cooling water technologies are not considered in the model calculations.

Irrigation sub-model: For the base year 2015, net and gross irrigation water requirements are computed on the extent of irrigated area as calculated by the LandSHIFT model (see Section 4.2.3) area equipped for irrigation based on the digital global map of irrigated areas around the year 2005 (Global Map of Irrigation Areas (GMIA) v.5 Siebert et al. 2013, 2015). However, future irrigation water demand is subject to changes in irrigated cropland, warming temperature and changing precipitation patterns. Future land use changes as well as the future extent and location of irrigated areas are determined with the LandSHIFT model, a well-tested global land use change model that has been successfully applied for different global and regional studies. Model results are performed for a set of two scenarios representing future land use changes (see Section 4.2.3, Figure 4-9) that are in line with the energy scenarios selected and described in detail in Section 4.1.2. In order to consider future climate change impacts, we use projections of four GCMs obtained through Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) and described in Section 4.3.1.2. We calculate irrigation water requirement per unit crop area under two RCPs (cf. Section 4.3.1.2). Irrigation efficiencies are kept constant at base year levels.

4.3.2.3 Key results

Producing electricity at thermal power plants requires substantial amounts of water during every stage of the energy cycle from mineral extraction to delivery of the fuel to the power plants (see also Section 3.1). But the greatest need for water comes from the cooling of turbines in the power plant. The amount of water required depends on the type and size of power plant, and especially in the kind of cooling. The two main types are "once-through cooling", in which water is used to cool the turbines and then discharged directly back to a river or pond, and "tower cooling" in which the turbines are cooled and the hot water is sent to a cooling tower, reused several times, and then eventually discharged from the plant. As a result, the water use intensity of a once-through flow cooling system is much higher compared to a tower cooling system. On the other hand, the fraction of water consumed is very small compared to the tower cooling system. Figure 4-16 shows the spatial distribution of water withdrawals and consumption used for cooling purposes in power plants and cleaning of solar panels for the year 2015 allocated to the 5 by 5 arcminute grid. According to the model results, about 657 km³ freshwater are withdrawn (~20 km³ consumed) for cooling thermoelectric and geothermal plants as well as for cleaning solar panels (see also Terrapon-Pfaff et al., 2020).

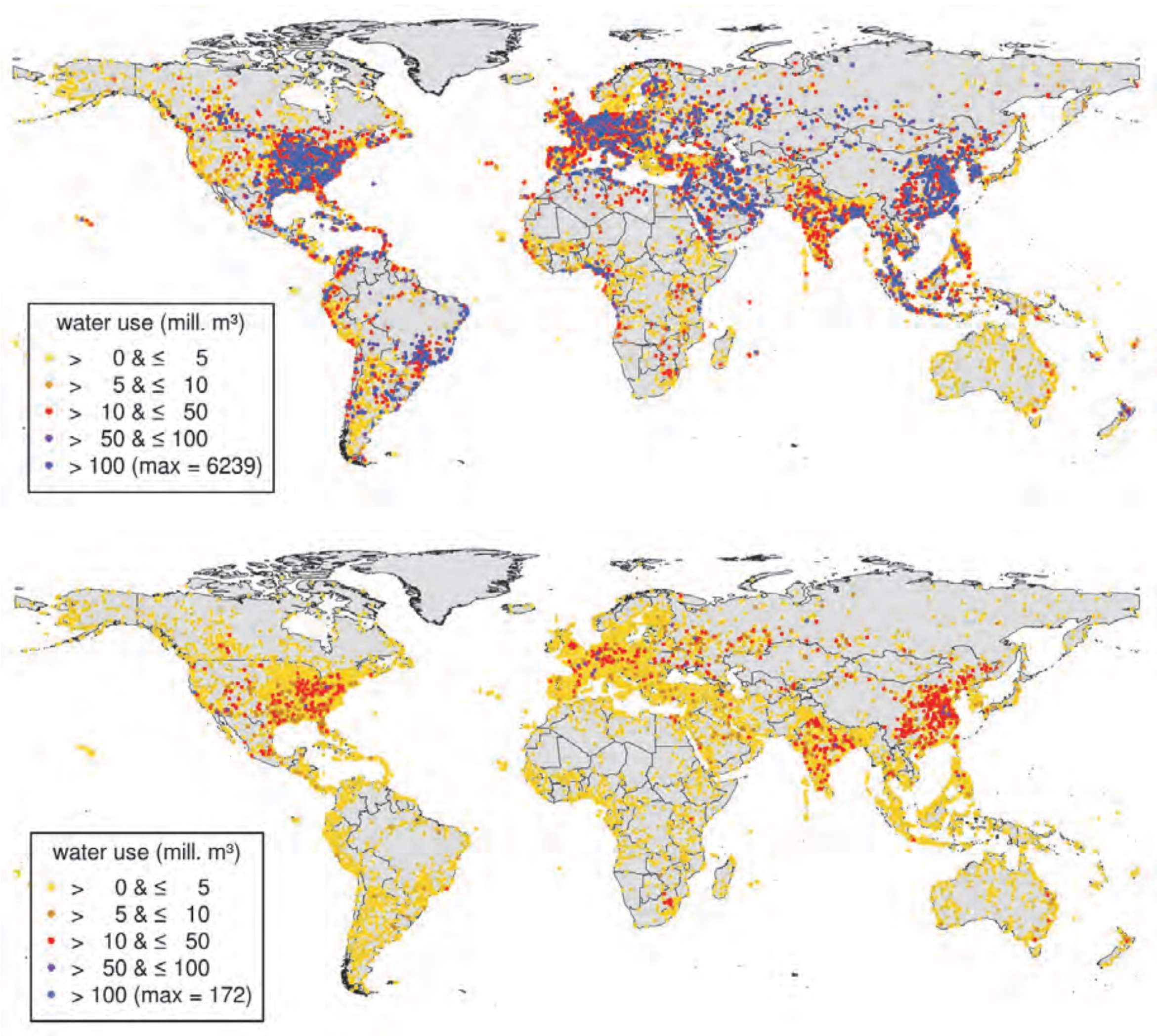

Figure 4-16: Water withdrawals (upper map) and water consumption (lower map) for the electricity production in the reference year 2015

In 2040, a clear change can be observed due to the share of electricity generation from renewable energy sources, particularly wind and photovoltaic sources (Figure 4-17). Water withdrawals are highest in the reference scenario (IEA CP), followed by GECO B2°C, IEA SD, and GP Adv. [R] (Figure 4-3). Our model results indicate an increase in water withdrawals in all scenarios compared to 2015 which differs compared to the calculation provided in Section 4.1.3. The differences result from the assumptions for the cooling technologies and the shift in combustion type between the power plants in the model. For example, today's coal-fired power plants will be replaced by biomass power plants in the future, i.e. the power plants will remain on site with existing cooling technology, but burn biomass instead of coal. Only in the GP Adv. [R] scenario are water withdrawals similar to those in 2015, although electricity production is expected to double.

Intensification and thus an increase in water withdrawals is very likely in all regions of the world in the IEA CP scenario. This is caused by the increase in electricity production based on fossil fuels. The trend in water demand varies between regions, but is particularly pronounced in the Middle East, India and China, as well as the USA (Figure 4-17a). In the GECO B2°C scenario, hotspots are located in India, China, Russia, and USA as a result of a significant increase in nuclear power generation (Figure 4-17c). Although an energy transition from coal-fired to nuclear-fired electricity generation leads to a reduction in CO_2 emissions, at the same time this scenario leads to a large increase in cooling water abstractions which is almost as high as in the IEA CP scenario. The IEA SD scenario still depends on energy sources which need cooling water for electricity production such as natural gas, uranium, and biomass. The dependence on these energy sources in the future and related cooling water needs become particularly evident in the USA, India and China Figure 4-17b). While the GP Adv. [R] scenario has the highest decarbonization potential, in some regions water withdrawals are expected to increase in the future due to the growth in geothermal, CSP, and biomass energy sources. This is evident in China and the west coast of the USA (Figure 4-17d).

a) b) c) d)

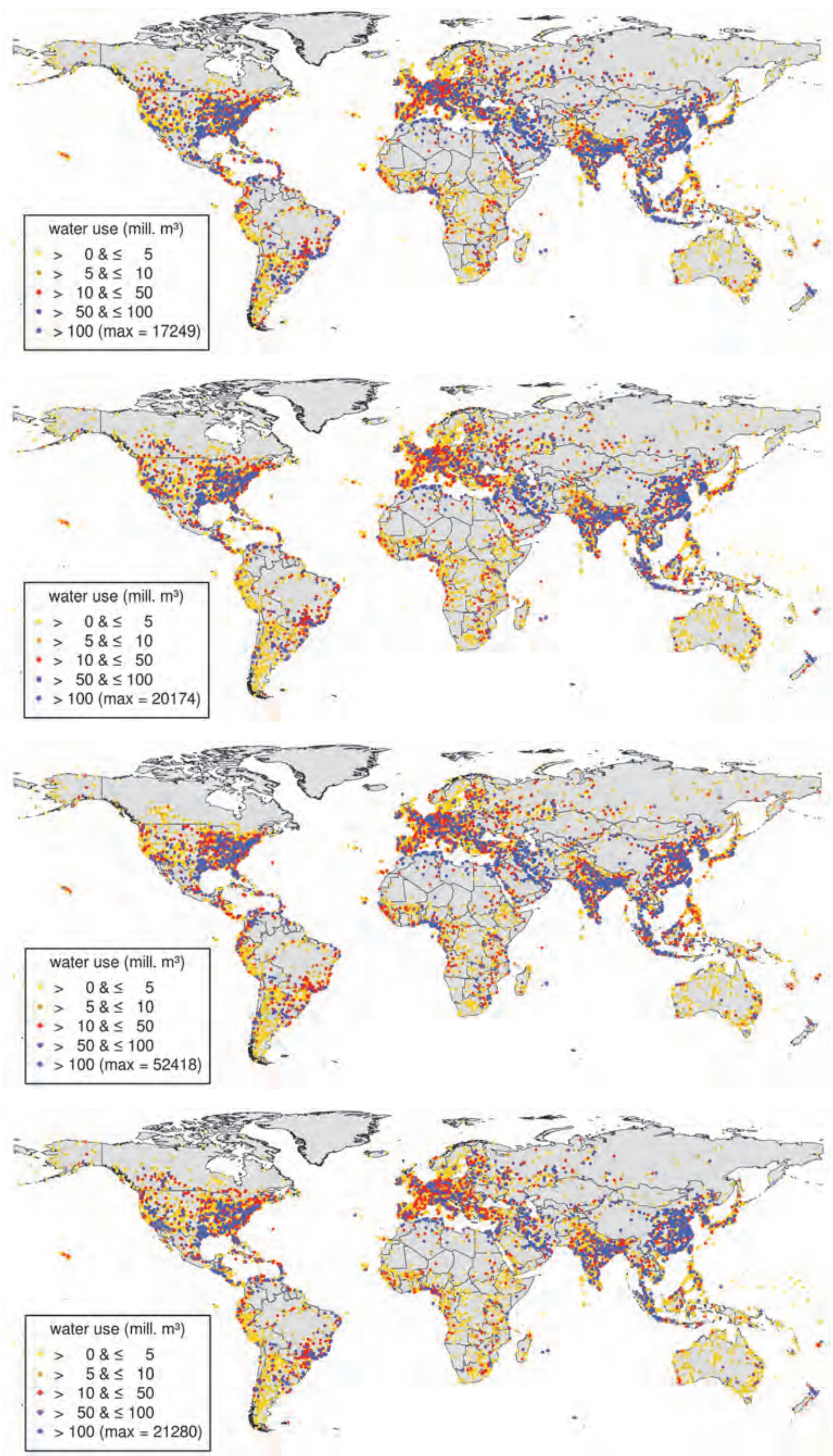

Figure 4-17: Water withdrawals for the electricity production in 2040 according to (a) the reference scenario (IEA CP) and three decarbonization scenarios: (b) IEA SD, (c) GECO B2°C, and (d) GP Adv. [R].

The main driving force of water withdrawals in the irrigation sector is the change in extent of irrigated area (see Section 4.2.3). The larger this area, the more water is needed for irrigation. In addition, climate change impacts represented by climate forcing data of four GCMs were taken into consideration to address climate uncertainties. To estimate the country scale irrigation water withdrawals, the per hectare crop requirements for water are multiplied by the area irrigated and then divided by the irrigation field efficiency (given on a country scale). Hence the improvement of irrigation efficiency will also drive changes in the amount of water withdrawn for irrigation. The expansion of irrigated land for the year 2040 was simulated by the LandSHIFT model for an SSP2-RCP2.6 and SSP2-RCP4.5 driven scenario. Future projections of water abstractions to irrigate agricultural land are calculated by WaterGAP3 on a grid cell level (5 x 5 arcminute geographical resolution). Grid cell results are then aggregated to regional numbers. Figure 4-18 depicts the WaterGAP3 sub-model results of gross irrigation water requirements according to geographic regions of the United Nations Environment Programme (UNEP Environmental Data Explorer) for the base year 2015 and 2040s as represented by the SSP2-RCP2.6 and SSP2-RCP4.5 scenarios. For the base year, a total of about 2,690 km^3 are abstracted for irrigation. Globally, the total gross irrigation water requirements increase by 63% between the base year and 2040s in SSP2-RCP2.6, and by 46% in SSP2-RCP4.5. The expansion in irrigation water withdrawals is primarily projected for Latin America and the Caribbean region and Africa, while the increase in irrigation water withdrawal tends to only slightly increase in West Asia and moderately in Europe.

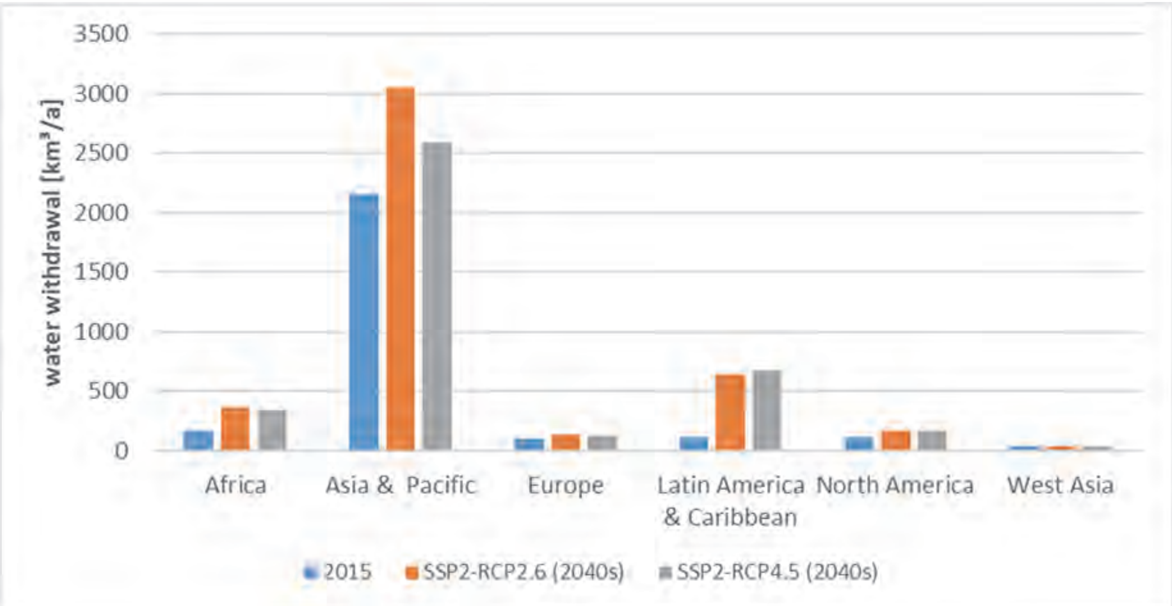

Figure 4-18: Irrigation water withdrawals calculated as ensemble mean for 2015 and 2040s (2032-2060) for RCP2.6 and RCP4.5 scenarios. Results consider climate forcing data of four GCMs and are summed-up for UNEP GEO regions.

Figure 4-19 shows the projection of gross irrigation water requirements on a grid-scale globally for the base year 2015 (upper map) and the SSP2-RCP2.6 (middle map) and SSP2-RCP4.5 (lower map) scenarios in 2040. Water withdrawals are already high in Asia, particularly India and China, but will further increase in both scenarios. Here, the increase is larger in the SSP2-RCP2 scenario compared to SSP2-RCP4.5 due to greater expansion of the irrigated area. The SSP2-RCP2.6 scenario leads to increases in water withdrawals of more than 40%, SSP2-RCP4.5 to 20%, respectively. Still, until 2040, an intensification of water withdrawn for irrigation purposes is likely in Latin America, but also in Eastern Africa where new area is expected to be equipped for irrigation. In Latin America, irrigation water withdrawals are expected to be five to six times higher than today whereas for the African continent water demand is expected to double in 2040. For East Africa in particular, a considerable increase in irrigation water demand by a factor of 10 is to be expected in order to support optimal crop growing in the future. Only minor changes in irrigation water requirements are expected in the future in Europe and West Asia. The reasons for increasing irrigation water requirements can be seen as the sum of an increase in total area irrigated, climate change and still quite low irrigation efficiency, which was kept constant to current conditions.

Although important for determining future irrigation water withdrawals, the future rates of technological change were kept constant to current levels, i.e. technological improvements of water use efficiency are not considered in this study. However, sustainable water and land management practices have the potential to lower the amount of water needed for irrigation by improving water use efficiencies and are subject to socio-economic developments and technological changes.

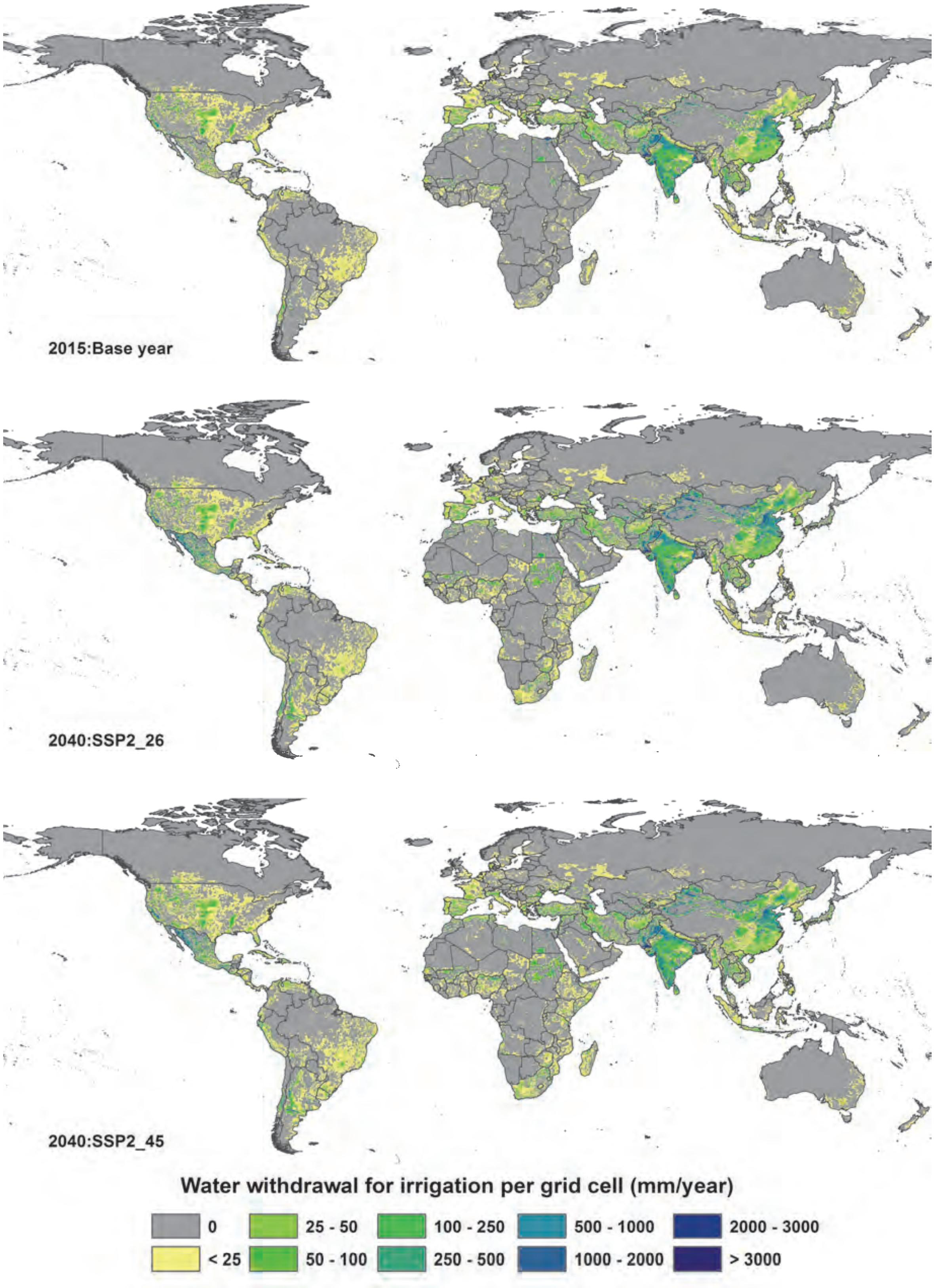

Figure 4-19: Water withdrawal per grid cell calculated as ensemble mean for the base year 2015 (top) and 2040s for SSP2-RCP2.6 (middle) and SSP2-RCP4.5 (bottom) taking into account climate forcing data of four GCMs and socio-economic developments of the SSP2 scenario.

4.4 Direct and Remote Impacts: A global Perspective

Authors: Martina Flörke, Ellen Kynast, Jenny Kupzig, Anna Schomberg, Alexander Lenz, Fengzhi He, Christiane Zarfl, Sonja C. Jähnig

4.4.1 Cooling Water Gap analysis

The objective of this analysis is to quantify the future 'Cooling Water Gap', here defined as the difference between the cooling water demand and water available for cooling. The global WaterGAP3 model is used to assess the possible gap between water requirements used for cooling purposes to produce electricity and to clean solar panels of, for example, CSP power plants, and the availability of water at the grid-level (i.e., 9 x 9 km at the equator). Water consumed by hydroelectric power plants is not considered in this analysis. WaterGAP3 is a suitable tool for this analysis because it computes water availability on a high resolution with global coverage (cf. Chapter 4.3), takes into account changes in water withdrawals in all economic sectors and climate change (Flörke et al., 2018), and can be used to examine the availability of water supply for energy systems under low flow conditions (Flörke et al., 2012). The Cooling Water Gap analysis identifies global hotspot locations where water demand for electricity production is likely not to be met in the future, i.e. where different types of conventional and renewable energy (e.g., CSP) may be constrained because of local water constraints. To perform the analysis, we first calculated monthly water availability for the 2040s (represented by the time period 2031-2060) based on the basis of daily climate input parameters from four GCMs and two RCPs (see Section 4.3.1). Second, we calculated sectoral monthly water consumption driven by the socio-economic data (SSP2 scenario, Section 4.2.2), electricity production data (energy scenarios, Section 4.1.2), land-use change (i.e., irrigated area, Section 4.2.3) and climate scenarios for the future on the grid scale. In a third step we determined the monthly cooling water gap as the difference between the long-term monthly mean water availability and cooling water abstractions within a grid cell. Finally, the monthly numbers are summed up to an annual value.

Further, we designed two different cases to assess the temporal development and spatial pattern of the cooling water gap under the different scenario conditions:

- Case 1: long-term natural flow conditions, i.e. total river discharge is available for cooling purposes.
- Case 2: long-term natural flow conditions reduced by upstream water consumption, i.e. the demand of the other sectors (agriculture, domestic, manufacturing) are served first.

Ensemble mean annual results of the cooling water gap considering case 1 assumptions are displayed in Figure 4-20. This figure synthesizes the results derived from the GCM ensemble for each energy-RCP combination, thus also illustrates the uncertainty ranges associated with the different future pathways.

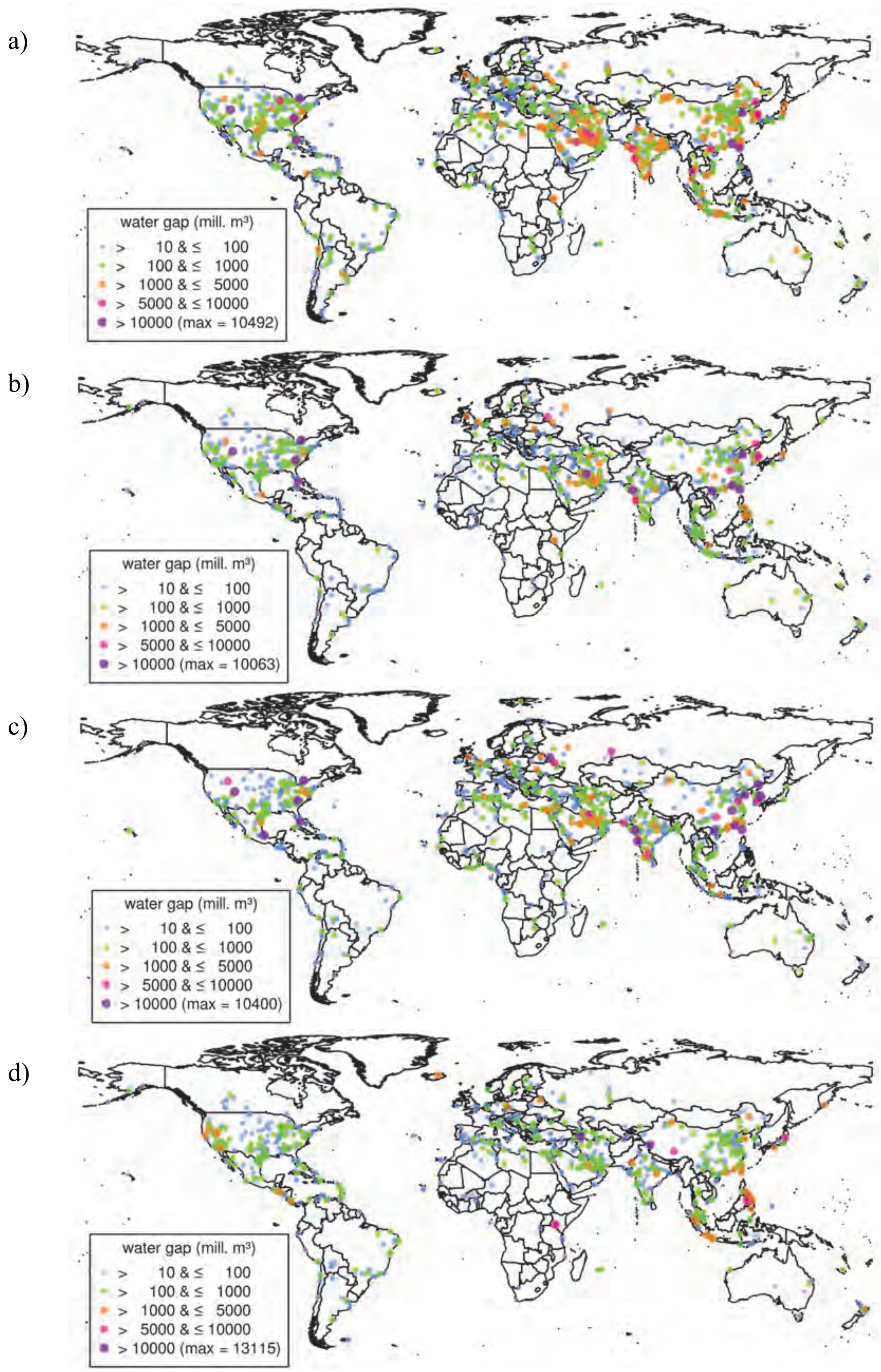

Figure 4-20: Locations of power plants where future cooling and cleaning water requirements may not be fulfilled in 2040. Model results for case 1 assumptions. (a) the reference scenario (IEA CP), (b) IEA SD, (c) GECO B2°C, and (d) GP Adv. [R].

The reference scenario (IEA CP) still builds on fossil and nuclear energy sources which will increase by about 56% until 2040. The cumulative electricity production, which depends on water resources for cooling purposes, will likely rise up to 29,500 TWh in 2040 (+53% compared to 2015). In the IEA CP, solar-based electricity production will be 8 times higher in 2040 compared to 2015 and water will be required to for cleaning the solar panels. Although the water usage is low for cleaning purposes, the cooling water demand (and consumption) of CSP power plants can be even higher than for coal-fired power plants with tower cooling technology. However, it must be taken into consideration that solar power plants in particular produce electricity in regions where sunshine duration is high but at the same time water resources are scarce (arid regions). As a result of the increasing thermal electricity production, water demand for cooling and cleaning is expected not to be fulfilled in many regions of the world (Figure 4-20a).

The decarbonization scenarios contribute to climate mitigation, but cooling water deficits cannot be avoided as visualized in Figure 4-20b-d. For example, the increase of electricity production based on nuclear power, gas, and biomass (GECO B2°C) leads to an increase in water abstractions, which in turn drives the cooling water gap. Both scenarios, IEA SD and GP Adv. [R], strongly reduce electricity production from fossil fuels and nuclear power and rely on biomass, geothermal energy, and CSP (among other renewable resources that do not require cooling water or water for panel cleaning). Large-scale use of these energy sources to achieve the energy transition cannot contribute to reducing the cooling water gap in many regions of the world.

Table 4-4 lists the Cooling Water Gap as share of the water demand potentially required for cooling and cleaning purposes in thermoelectric and solar-based power plants in 2040. Globally, about 44% to 59% of the water demand will not be satisfied in the future at current power plant locations. Hence, huge efforts have to be taken to improve or develop new technologies to safe water and to build new power plants in regions where renewable freshwater resources do not limit power generation. Comparing case 1 and 2 highlights the need to also avoid competition with other water use sectors, in particular competing water abstractions for irrigation (see Table 4-4, case 2), which is the main consumer of upstream water resources.

Summing up, it can be noted that modelling tools and spatio-temporal explicit indicator analyses are important to identify trade-offs between energy- and water-related goals. These methods in combination with scenarios that draw possible future developments of the energy and agricultural sectors (particularly irrigation) can already point to changes that need to be prevented. Here, the analysis of interlinkages between available water resources and electricity generation are key to avoid trade-offs (i.e., shortages, losses) in the long-term. Competition with other water use sectors for the same resource may lead to conflicts in the future. Therefore, aspects of water requirements of future energy systems have to be considered at the local and global levels in order to achieve a sustainable energy transition.

Table 4-4: Future Cooling Water Gap as percentage share of water abstractions to satisfy the demand at power plant locations. The percentages represent ensemble means of the cooling water gap as water availability was determined for four GCMs.

Scenario	RCP	Cooling Water GAP [%]	
		Case 1	Case 2
IEA CP	4.5	46.2	51.2
IEA SD	2.6	47.6	51.8
GECO B2°C	2.6	55.3	58.6
GP Adv. [R]	2.6	44	49

As even energy scenarios for decarbonization still depend on water consuming technologies for electricity generation, losses in electricity production can be expected due to water shortages as a result of climate change and higher demands. Rising river water temperatures will put additional pressure on the energy industry in the future. The ambitious CO_2 reduction scenario GP Adv. [R], for example, features a substantial increase in the share of renewable energy in the global energy mix, which contributes to CO_2 reduction but may also exacerbate water scarcity.

Overall, the principal cause of cooling water deficits is the increase in water abstractions for cooling purposes and also for cleaning solar panels in water scarce regions. The increase in water withdrawal correlates directly with the rising demand for electricity that is expected in the future due to increasing electrification. Climate change will exacerbate the situation in the medium- and long-term which is expected to become more severe if the change in water consumption of other water users is considered, too.

In the future, cooling water shortages may occur, especially when river discharge is low and water temperature is close to or above the threshold set for water intake in national legislation. This strongly depends on the availability of water, not only in sufficient amounts but also at the right time throughout the year. On the other side, in water scarce regions, water abstractions for electricity production will always compete with other users.

The availability of water resources must also be considered in case of profound changes in energy systems. Investments in new technologies, improvements in water and energy efficiency and the examination of suitable sites are prerequisite for achieving sustainable water and energy security today and in the future. Next to technological advances, further measures should include the reduction of energy consumption.

However, this analysis is also subject to major limitations. In particular, the power plant-specific information on the cooling system (if not available in the database), the use of average water use intensities as well as uncertainties in the allocation of the sites should be mentioned. New power plants were built at the same location and equipped with the same cooling technology as the outdated ones, i.e. renewable energy sources (e.g. biomass) replaced fossil fuels directly at their power plant sites. Furthermore, technological improvements were not considered in the simulations.

Although subject to limitations, this analysis highlights the interlinkages between water resources and the energy sector and the need for a comprehensive approach to identify and assess the potential trade-offs and synergies between SDG 6 and SDG 7.

4.4.2 WSF and ESA

The spatially explicit analyses of the Water Scarcity Footprint (WSF) and other environmental impacts (ESA) in Chapter 3 lead to the following conclusions on a global perspective:

1. Only selected contributions are on-site, the far greater part of the environmental impacts takes place in the preceding chains and thus can be characterized as a remote impact.
2. International preceding chains are complex and far-reaching and need to be constantly further regionalized in order to be able to allocate contributions and identify hotspots. This is especially true for mining resources such as gravel and sand, fossil fuels such as natural gas, the chemical industry, and energy wood, as the studies conducted here suggest.
3. Local actors can only exert little influence on international supply chains, because this is only possible to a limited extent. Nevertheless, consideration of the entire supply chain should come more and more into focus in the near future, both at the level of local actors and at higher levels up to the international community. Local actors can make an active contribution to reducing the environmental impact of energy production plants, especially through careful planning in advance, i.e. evaluating measures to reduce raw material and water requirements.
4. In order to be able to implement the energy transition globally in a sustainable manner, problem shifting must be avoided. This is only possible if potential teleconnections for energy generation plants are identified in advance. For this purpose, a global and a regional perspective must be adopted at the same time, the former in order to be able to analyse the global value chains, i.e. the upstream activities, and the latter, i.e. the downstream activities, in order to be able to assess the regional impacts of each of the components of the upstream chain.

4.4.3 Megafauna analysis

Given the large amount of potential capacity across the world (Hoes, Meijer, van der Ent, & van de Giesen, 2017) and its relatively lower cost compared to other renewable energy productions (e.g. solar, geothermal, wind, and biofuel; (IEA, 2020c), hydropower has received major attention with over 3500 dams under construction or planned, however, often in basins with high level of freshwater biodiversity (Hermoso, 2017; Winemiller et al., 2016; C. Zarfl, Lumsdon, Berlekamp, Tydecks, & Tockner, 2015). Besides electricity generation, hydropower plants and associated dams and reservoirs often provide other services including flood protection, water supply for drinking or irrigation, and supporting recreational activities and aquaculture (Berga, 2016).

Although it has often been promoted as clean green energy, hydropower has a major influence on the environment (Botelho et al., 2017). Obviously, dams alter natural flow regimes but also impede transport of nutrients (e.g. carbon, nitrogen, phosphorus, and silicon) and sediments along rivers (Gupta et al., 2012; Maavara et al., 2020). Considerable amounts of greenhouse gas emissions could be released from reservoirs and downstream rivers of dams (Guérin et al., 2006; Maavara et al., 2020). Furthermore, dams block movement pathways of freshwater species, posing profound impacts on freshwater biodiversity (Winemiller et al., 2016; Hermoso, 2017; Couto & Olden, 2018). Within the WANDEL project, we used freshwater megafauna (i.e. freshwater animals that can reach a body mass of 30 kg or more; He et al., 2017) as surrogates to explore the potential impacts of dams and reduced river connectivity on freshwater biodiversity, with a two-step approach.

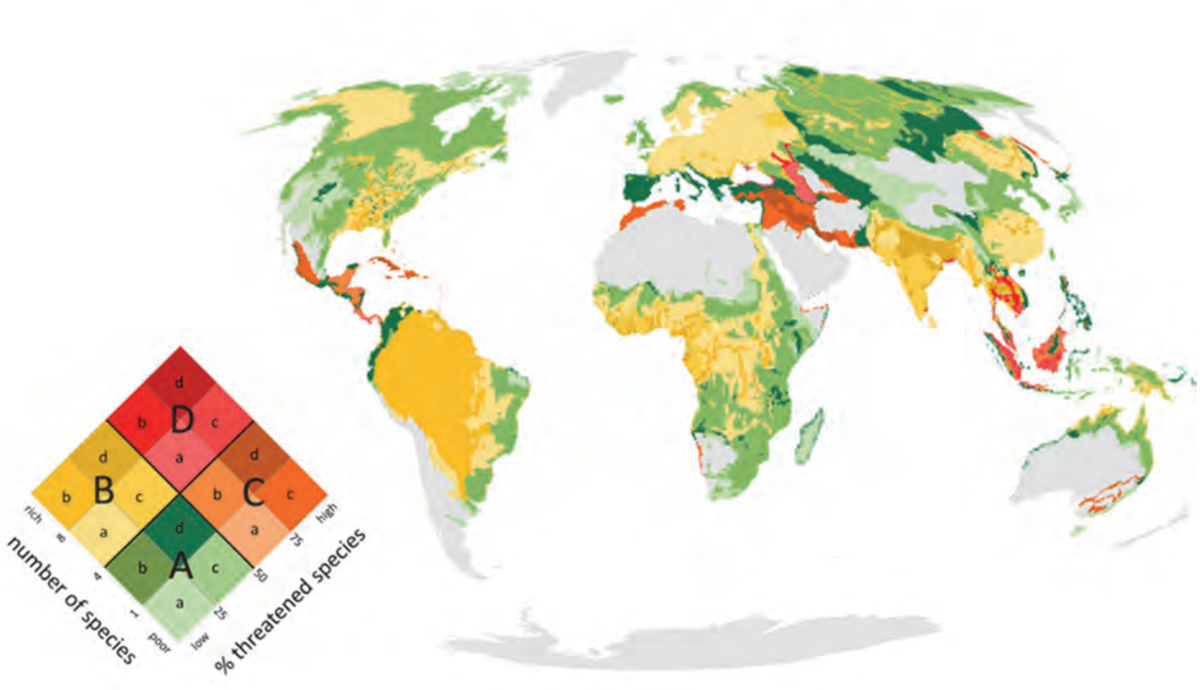

Figure 4-21: Choropleth map of sub-catchments (HydroBASINS level 8) according to species richness and threat status on a global scale (Zarfl et al., 2019)

In the first step, we combined, at the global scale, comprehensive information on 6,862 existing large dams (i.e., at least 15 m high and 0.1 km3 storage capacity) from the GRanD database (Lehner et al., 2011) and 3,682 future hydropower dams (i.e., with a capacity over 1 MW) from the FHReD database (C. Zarfl et al., 2015) with data of 207 freshwater megafauna taxa (He et al., 2018). We used HydroBASINS level-8 sub-catchment as spatial units to overlap distributions of dams and freshwater megafauna taxa and considered their conservation status assigned by the International Union for the Conservation of Nature (IUCN)

Red List of Threatened Species (here after referred to as IUCN Red List; IUCN (2016), version 2016-3). In total, 3,729 existing large dams are located in sub-catchments with fewer than five freshwater megafauna taxa and a proportion of less than 50% of threatened taxa (i.e. assessed as Critically Endangered, Endangered, or Vulnerable on the IUCN Red List). In addition, 1,358 hydropower dams are planned in these sub-catchments (category A in Figure 4-21). Sub-catchments with fewer than five freshwater megafauna taxa and a share of less than 50% of threatened taxa (category B) already have 2,527 dams built within them and have 1,894 hydropower dams planned. In addition, sub-catchments with high freshwater megafauna richness (i.e., at least five species) and high share (i.e., over 50%) of threatened taxa (category D) also expect a considerable number of future hydropower dams. For example, the Mekong Basin, a diversity hotspot of freshwater megafauna (i.e., 22 taxa) with a high share of threatened taxa (i.e., over 50%) will expect 30 hydropower dams in the future.

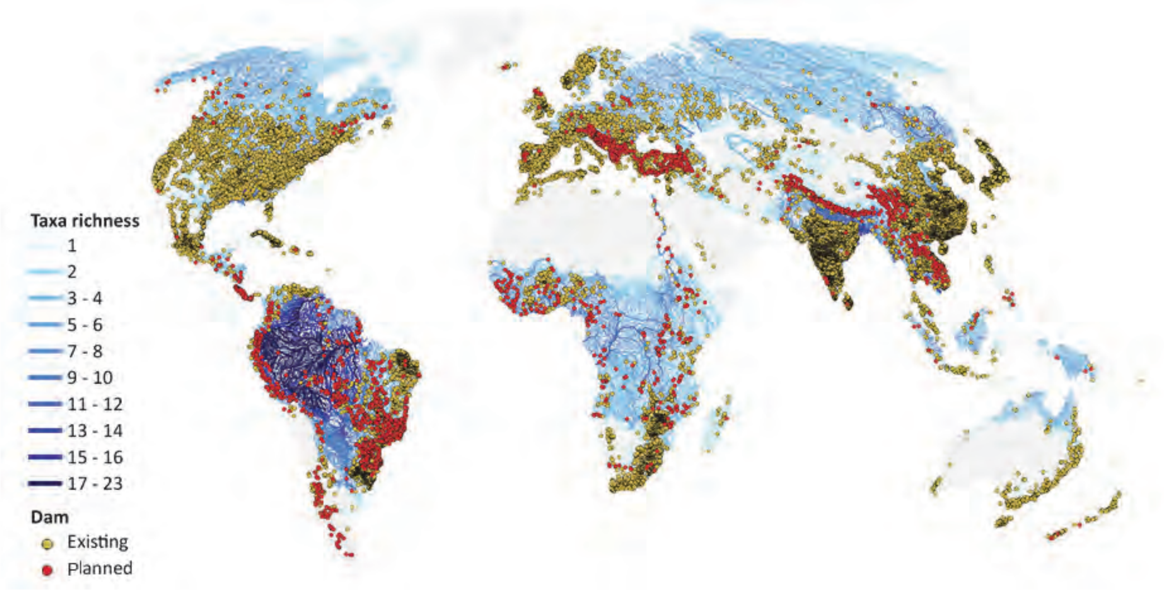

Figure 4-22: Taxa richness of freshwater megafauna in rivers over 100 km and distributions of existing and planned dams.

In the second step, we included more existing medium-size dams from the GOODD database (Mulligan et al., 2020) in addition to those from GRanD and FHReD databases. A total of 23,579 dams were included in our analysis (Figure 4-22). Here we focused on river sections themselves, accounting for effects on connectivity of rivers and associated riparian areas. Moreover, we considered four dimensions (i.e., longitudinal, lateral, vertical, and temporal) of river connectivity and other stressors (e.g., water consumption and infrastructure along rivers) that can also reduce river connectivity in these dimensions. Following Grill et al. (2019), we measured the connectivity status of river reaches inhabited by freshwater megafauna using the Connectivity Status Index (CSI) for two scenarios: a current (considering only existing dams) and a future (including both existing and future dams) scenario. The CSI included information on different stressors including fragmentation, flow regulation, sediment trapping, water abstraction, and urban areas and road density along rivers. Rivers with all sections having CSI values ≥ 95% are considered as free-flowing rivers (FFRs; Grill et al., 2019). Patterns of river connectivity vary among basins with high level of freshwater megafauna diversity under the current scenario. For example, most rivers in the Amazon, Orinoco, and Congo basins are free-flowing. However, in Danube, Mississippi, and Yangtze basins, most rivers with a length over 500 km are highly fragmented. If all the planned dams were built, hundreds of current FFRs that harbor freshwater megafauna would lose their free-flowing status in the future, particularly those large rivers over 500 km. These rivers are mainly in basins with high levels of freshwater megafauna diversity, including Amazon, Mekong, Ganges, Congo, and Irrawaddy. Freshwater megafauna species such as river dolphins, manatees, large migratory catfish and giant turtles are subject to threats of further reduced river connectivity.

Our results suggest an urgent need to balance biodiversity conservation with dam development in order to fulfil international agreements, including the European Water Framework Directive, the SDGs (e.g., SDG 6 on restoration of freshwater ecosystems and SDG 15 on species conservation) and the Aichi biodiversity goals. Conservation actions to safeguard freshwater megafauna and overall freshwater biodiversity may include prioritizing locations and operations of planned dams and updates of IUCN Red List assessments in those regions subject to future loss of river connectivity.

4.5 References Chapter 4

Bayerisches Landesamt für Umwelt - LfU Bayern. (2021, June 18). https://www.lfu.bayern.de/index.htm

BfG - The GRDC. (2021, June 18). https://www.bafg.de/GRDC/EN/Home/homepage_node.html

Ahmad, T., & Zhang, D. (2020). A critical review of comparative global historical energy consumption and future demand: The story told so far. *Energy Reports*, *6*, 1973–1991. https://doi.org/10.1016/j.egyr.2020.07.020

Alcamo, J., Schaldach, R., Koch, J., Kölking, C., Lapola, D., & Priess, J. (2011). Evaluation of an integrated land use change model including a scenario analysis of land use change for continental Africa. *Environmental Modelling & Software*, *26*(8), 1017–1027. https://doi.org/10.1016/j.envsoft.2011.03.002

Alexander, P., Prestele, R., Verburg, P. H., Arneth, A., Baranzelli, C., Batista E Silva, F., Brown, C., Butler, A., Calvin, K., Dendoncker, N., Doelman, J. C., Dunford, R., Engstrom, K., Eitelberg, D., Fujimori, S., Harrison, P. A., Hasegawa, T., Havlik, P., Holzhauer, S., . . . Rounsevell, M. D. A. (2016). Assessing uncertainties in land cover projections. *Global Change Biology*.

Andreadis, K. M., Schumann, G. J.-P., & Pavelsky, T. (2013). A simple global river bankfull width and depth database. *Water Resources Research*, *49*(10), 7164–7168. https://doi.org/10.1002/wrcr.20440

Bauer, N., Calvin, K., Emmerling, J., Fricko, O., Fujimori, S., Hilaire, J., Eom, J., Krey, V., Kriegler, E., Mouratiadou, I., Sytze de Boer, H., van den Berg, M., Carrara, S., Daioglou, V., Drouet, L., Edmonds, J. E., Gernaat, D., Havlik, P., Johnson, N., . . . van Vuuren, D. P. (2017). *Shared Socio-Economic Pathways of the Energy Sector – Quantifying the Narratives* (Vol. 42). https://reader.elsevier.com/reader/sd/pii/S0959378016301224?token=ED221393CF6A114D0139270D4F79D2622F6D838842A7CB46F88D68D1581619C7EE71C583259285B9080DCB3B83594F6D&originRegion=eu-west-1&originCreation=20210621102002 https://doi.org/10.1016/j.gloenvcha.2016.07.006

Beek, T. aus der, Flörke, M., Lapola, D. M., Schaldach, R., Voß, F., & Teichert, E. (2010). Modelling historical and current irrigation water demand on the continental scale: Europe. *Advances in Geosciences*, *27*, 79–85. https://doi.org/10.5194/adgeo-27-79-2010

Berga, L. (2016). The Role of Hydropower in Climate Change Mitigation and Adaptation: A Review. *Engineering*, *2*(3), 313–318. https://doi.org/10.1016/J.ENG.2016.03.004

Bondeau, A., Smith, P. C., Zaehle, S., Schapoff, S., Lucht, W., Cramer, W., Gerten, D., Lotze-Campen, H., Müller, C., Reichstein, M., & Smith, B. (2007). Modelling the role of agriculture for the 20th century global terrestrial carbon balance. *Global Change Biology*, *13*(3), 679–706. https://doi.org/10.1111/j.1365-2486.2006.01305.x

Botelho, A., Ferreira, P., Lima, F., Pinto, L. M. C., & Sousa, S. (2017). *Assessment of the environmental impacts associated with hydropower* (Vol. 70). https://reader.elsevier.com/reader/sd/pii/S1364032116310462?token=8A7A47FB99CDEFADF518DDAAEF99DFA5CF6F647726C138FCD4DACC1842EB2D94E5C66894DEFD7D1026950DA5B12F93BA&originRegion=eu-west-1&originCreation=20210621112400 https://doi.org/10.1016/j.rser.2016.11.271

Brauman, K. A., Richter, B. D., Postel, S., Malsy, M., & Flörke, M. (2016). Water depletion: An improved metric for incorporating seasonal and dry-year water scarcity into water risk assessments. *Elementa: Science of the Anthropocene*, *4*, 83. https://doi.org/10.12952/journal.elementa.000083

Couto, T. B. A., & Olden, J. D. (2018). Global proliferation of small hydropower plants - science and policy. *Frontiers in Ecology and the Environment*, *16*(2), 91–100. https://doi.org/10.1002/fee.1746

Döll, P. (2009). Vulnerability to the impact of climate change on renewable groundwater resources: A global-scale assessment. *Environmental Research Letters*, *4*(3). https://doi.org/10.1088/1748-9326/4/3/035006

Döll, P., & Siebert, S. (2002). Global modeling of irrigation water requirements. *Water Resources Research*, *38*(4), 8-1-8-10. https://doi.org/10.1029/2001WR000355

Döll, P., & Vassolo, S. (2004). Global-scale vs. regional-scale scenario assumptions: implications for estimating future water withdrawals in the Elbe River basin. *Regional Environmental Change*, *4*(4), 169–181. https://doi.org/10.1007/s10113-004-0074-y

Eisner, S., Flörke, M., Chamorro, A., Daggupati, P., Donnelly, C., Huang, J., Hundecha, Y., Koch, H., Kalugin, A., Krylenko, I., Mishra, V., Piniewski, M., Samaniego, L., Seidou, O., Wallner, M., & Krysanova, V. (2017). An ensemble analysis of climate change impacts on streamflow seasonality across 11 large river basins. *Climatic Change*, *141*(3), 401–417. https://doi.org/10.1007/s10584-016-1844-5

Eisner, S. (2016). *Comprehensive evaluation of the WaterGAP3 model across climatic, physiographic, and anthropogenic gradients*. Ph.D. thesis. University of Kassel.

ESA Climate Change Initiative. (2017). *Land Cover led by UCLouvain (2017).* http://maps.elie.ucl.ac.be/CCI/viewer/download.php

European Commission. Joint Research Centre. (2017). *Global energy and climate outlook 2017: How climate policies improve air quality: Global energy trends and ancillary benefits of the Paris Agreement*. Publications Office. https://doi.org/10.2760/34111

FAOSTAT. (2021, May 5). http://www.fao.org/faostat/en/#data/QC

Flörke, M., Bärlund, I., & Kynast, E. (2012). Will climate change affect the electricity production sector? A European study. *Journal of Water and Climate Change*, *3*(1), 44–54. https://doi.org/10.2166/wcc.2012.066

Flörke, M., Kynast, E., Bärlund, I., Eisner, S., Wimmer, F., & Alcamo, J. (2013). Domestic and industrial water uses of the past 60 years as a mirror of socio-economic development: A global simulation study. *Global Environmental Change*, *23*(1), 144–156. https://doi.org/10.1016/j.gloenvcha.2012.10.018

Flörke, M., Schneider, C., & McDonald, R. I. (2018). Water competition between cities and agriculture driven by climate change and urban growth. *Nature Sustainability*, *1*(1), 51–58. https://doi.org/10.1038/s41893-017-0006-8

Food and Agriculture Organization of the United Nations. (2021). *FAOSTAT: database*. http://www.fao.org/faostat/en/#data/QC

Frieler, K., Lange, S., Piontek, F., Reyer, C. P. O., Schewe, J., Warszawski, L., Zhao, F., Chini, L., Denvil, S., Emanuel, K., Geiger, T., Halladay, K., Hurtt, G., Mengel, M., Murakami, D., Ostberg, S., Popp, A., Riva, R., Stevanovic, M., . . . Yamagata, Y. (2017). Assessing the impacts of 1.5 °C global warming – simulation protocol of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP2b). *Geoscientific Model Development*, *10*(12), 4321–4345. https://doi.org/10.5194/gmd-10-4321-2017

Göpel, J., Schüngel, J., Stuch, B., & Schaldach, R. (2020). Assessing the effects of agricultural intensification on natural habitats and biodiversity in Southern Amazonia. *PloS One*, *15*(11), e0225914. https://doi.org/10.1371/journal.pone.0225914

Greenpeace, & Teske, S., Muth, J., Sawyer, S., Pregger, T., Simon, S., Naegler, T., … & Graus, W. H. J. (Eds.). *energy [r]evolution - A sustainable world energy outlook.*

Grill, G., Lehner, B., Thieme, M., Geenen, B., Tickner, D., Antonelli, F., Babu, S., Borrelli, P., Cheng, L., Crochetiere, H., Ehalt Macedo, H., Filgueiras, R., Goichot, M., Higgins, J., Hogan, Z., Lip, B., McClain, M. E., Meng, J., Mulligan, M., . . . Zarfl, C. (2019). Mapping the world's free-flowing rivers. *Nature*, *569*(7755), 215–221. https://doi.org/10.1038/s41586-019-1111-9

Guérin, F., Abril, G., Richard, S., Burban, B., Reynouard, C., Seyler, P., & Delmas, R. (2006). Methane and carbon dioxide emissions from tropical reservoirs: Significance of downstream rivers. *Geophysical Research Letters*, *33*(21). https://doi.org/10.1029/2006GL027929

Gupta, H., Kao, S.-J., & Dai, M. (2012). *The role of mega dams in reducing sediment fluxes: A case study of large Asian rivers* (464-465). https://reader.elsevier.com/reader/sd/pii/S0022169412006397?token=28BC127271DEE48144727E41E8790D7843B5026AD81D547F547230634912DB478F73A7A3198424303999BEE660164ECC&originRegion=eu-west-1&originCreation=20210622070850 https://doi.org/10.1016/j.jhydrol.2012.07.038

He, F., Bremerich, V., Zarfl, C., Geldmann, J., Langhans, S. D., David, J. N. W., Darwall, W., Tockner, K., & Jähnig, S. C. (2018). Freshwater megafauna diversity: Patterns, status and threats. *Diversity and Distributions*, *24*(10), 1395–1404. https://doi.org/10.1111/ddi.12780

He, F., Zarfl, C., Bremerich, V., Henshaw, A., Darwall, W., Tockner, K., & Jähnig, S. C. (2017). Disappearing giants: A review of threats to freshwater megafauna. *Wiley Interdisciplinary Reviews: Water*, *4*(3), e1208. https://doi.org/10.1002/wat2.1208

Heistermann, M. (2006). *Modelling the Global Dynamics of Rain-fed and Irrigated Croplands* [Dissertation], University of Kassel, Germany.

Hempel, S., Frieler, K., Warszawski, L., Schewe, J., & Piontek, F. (2013). A trend-preserving bias correction – the ISI-MIP approach. *Earth System Dynamics*, *4*(2), 219–236. https://doi.org/10.5194/esd-4-219-2013

Hermoso, V. (2017). Freshwater ecosystems could become the biggest losers of the Paris Agreement. *Global Change Biology*, *23*(9), 3433–3436. https://doi.org/10.1111/gcb.13655

Hinz, R., Sulser, T. B., Huefner, R., Mason-D'Croz, D., Dunston, S., Nautiyal, S., Ringler, C., Schuengel, J., Tikhile, P., Wimmer, F., & Schaldach, R. (2020). Agricultural Development and Land Use Change in India: A Scenario Analysis of Trade-Offs Between UN Sustainable Development Goals (SDGs). *Earth's Future*, *8*(2). https://doi.org/10.1029/2019EF001287

Hoes, O. A. C., Meijer, L. J. J., van der Ent, R. J., & van de Giesen, N. C. (2017). Systematic high-resolution assessment of global hydropower potential. *PLOS ONE*, *12*(2), e0171844. https://doi.org/10.1371/journal.pone.0171844

Hrachowitz, M., Savenije, H.H.G., Blöschl, G., McDonnell, J. J., Sivapalan, M., Pomeroy, J. W., Arheimer, B., Blume, T., Clark, M. P., Ehret, U., Fenicia, F., Freer, J. E., Gelfan, A., Gupta, H. V., Hughes, D. A., Hut, R. W., Montanari, A., Pande, S., Tetzlaff, D., . . . Cudennec, C. (2013). A decade of Predictions in Ungauged Basins (PUB)—a review. *Hydrological Sciences Journal*, *58*(6), 1198–1255. https://doi.org/10.1080/02626667.2013.803183

IEA. (2021, June 18). *Energy intensity – SDG7: Data and Projections – Analysis - IEA*. https://www.iea.org/reports/sdg7-data-and-projections/energy-intensity

IEA. (2021, June 22). *SDG7: Data and Projections – Analysis - IEA*. https://www.iea.org/reports/sdg7-data-and-projections

IEA, & International Energy Agency. *World Energy Outlook-2017*.

IEA Irena. (2021, June 18). *Power Generation Costs*. https://www.irena.org/costs/Power-Generation-Costs

International Energy Agency - IEA. World Energy Outlook 2016 - Excerpt - Water-Energy Nexus.

International Food Policy Research Institute. (2019). *Global Spatially-Disaggregated Crop Production Statistics Data for 2010 Version 2.0.* Harvard Dataverse, V4.

International Renewable Energy Agency. *Renewable Energy in the Water, Energy and Food Nexus.*

IUCN Global Species Programme Red List Unit. (2021, June 18). *IUCN Red List of Threatened Species*. https://www.iucnredlist.org/

Jin, Y., Behrens, P., Tukker, A., & Scherer, L. (2019). Water use of electricity technologies: A global meta-analysis. *Renewable and Sustainable Energy Reviews*, *115*, 109391. https://doi.org/10.1016/j.rser.2019.109391

JRC, Kitous, A., Keramidas, K., Vandyck, T., Saveyn, B., van Dingenen, R., Spadaro, J., & Holland, M. (2021, June 21). *Global energy and climate outlook 2017 - Publications Office of the EU*. https://op.europa.eu/en/publication-detail/-/publication/409509ca-bd28-11e7-a7f8-01aa75ed71a1/language-en

KC, S., & Lutz, W. (2017). The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. *Global Environmental Change*, *42*, 181–192. https://doi.org/10.1016/j.gloenvcha.2014.06.004

Koch, H., & Vögele, S. (2009). Dynamic modelling of water demand, water availability and adaptation strategies for power plants to global change. *Ecological Economics*, *68*(7), 2031–2039. https://doi.org/10.1016/j.ecolecon.2009.02.015

Koch, J., Schaldach, R., & Göpel, J. (2019). Can agricultural intensification help to conserve biodiversity? A scenario study for the African continent. *Journal of Environmental Management*, *247*, 29–37. https://doi.org/10.1016/j.jenvman.2019.06.015

Kriegler, E., Bauer, N., Popp, A., Humpenöder, F., Leimbach, M., Strefler, J., Baumstark, L., Bodirsky, B. L., Hilaire, J., Klein, D., Mouratiadou, I., Weindl, I., Bertram, C., Dietrich, J.-P., Luderer, G., Pehl, M., Pietzcker, R., Piontek, F., Lotze-Campen, H., . . . Edenhofer, O. (2017). Fossil-fueled development (SSP5): An energy and resource intensive scenario for the 21st century. *Global Environmental Change*, *42*, 297–315. https://doi.org/10.1016/j.gloenvcha.2016.05.015

Lange, S. (2018). Bias correction of surface downwelling longwave and shortwave radiation for the EWEMBI dataset. *Earth System Dynamics*, *9*(2), 627–645. https://doi.org/10.5194/esd-9-627-2018

Lange, S. (2019). *Earth2observe, WFDEI and ERA-Interim data Merged and Bias-corrected for ISIMIP (EWEMBI)*. GFZ Data Services. https://publications.pik-potsdam.de/pubman/faces/ViewItemFullPage.jsp;jsessionid=S5nPYHwGTaOHIPhT9Cm5iPNetmPfoS_lzbtyrY_e.se97?itemId=item_23442_4&view=EXPORT https://doi.org/10.5880/pik.2019.004

Lehner, B., & Döll, P. (2004). Development and validation of a global database of lakes, reservoirs and wetlands. *Journal of Hydrology*, *296*(1-4), 1–22. https://doi.org/10.1016/j.jhydrol.2004.03.028

Lehner, B., Liermann, C. R., Revenga, C., Vörösmarty, C., Fekete, B., Crouzet, P., Döll, P., Endejan, M., Frenken, K., Magome, J., Nilsson, C., Robertson, J. C., Rödel, R., Sindorf, N., & Wisser, D. (2011). High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management. *Frontiers in Ecology and the Environment*, *9*(9), 494–502. https://doi.org/10.1890/100125

Lehner, B., Verdin, K., & Jarvis, A. (2008). New Global Hydrography Derived From Spaceborne Elevation Data. *Eos, Transactions American Geophysical Union*, *89*(10), 93. https://doi.org/10.1029/2008EO100001

Maavara, T., Chen, Q., van Meter, K., Brown, L. E., Zhang, J., Ni, J., & Zarfl, C. (2020). River dam impacts on biogeochemical cycling. *Nature Reviews Earth & Environment*, *1*(2), 103–116. https://doi.org/10.1038/s43017-019-0019-0

Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., van Vuuren, D. P., Carter, T. R., Emori, S., Kainuma, M., Kram, T., Meehl, G. A., Mitchell, J. F. B., Nakicenovic, N., Riahi, K., Smith, S. J., Stouffer, R. J., Thomson, A. M., Weyant, J. P., & Wilbanks, T. J. (2010). The next generation of scenarios for climate change research and assessment. *Nature*, *463*(7282), 747–756. https://doi.org/10.1038/nature08823

Mulligan, M., van Soesbergen, A., & Sáenz, L. (2020). Goodd, a global dataset of more than 38,000 georeferenced dams. *Scientific Data*, *7*(1), 31. https://doi.org/10.1038/s41597-020-0362-5

Ramankutty, N., Hertel, T., Lee, H.-L., & Rose, S. K. (2007). Global agricultural land-use data for integrated assessment modeling. In M. E. Schlesinger, H. S. Kheshgi, J. Smith, F. C. de La Chesnaye, J. M. Reilly, T. Wilson, & C. Kolstad (Eds.), *Human-Induced Climate Change* (pp. 252–265). Cambridge University Press. https://doi.org/10.1017/CBO9780511619472.025

ResearchGate. (2018, August 1). *(PDF) Update of the digital global map of irrigation areas to version 5*. https://www.researchgate.net/publication/264556183_Update_of_the_digital_global_map_of_irrigation_areas_to_version_5

Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J. C., KC, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., . . . Tavoni, M. (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, *42*, 153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009

Richard G. Allan, Luis S. Pereira, Dirk Raes, & Martin Smith. (1998). *Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56* (Vol. 56). https://www.researchgate.net/publication/235704197_Crop_evapotranspiration-Guidelines_for_computing_crop_water_requirements-FAO_Irrigation_and_drainage_paper_56

Rohwer, J., Gerten, D., & Lucht, W. (2007). *Development of Funktional Irrigation Types for Improved Global Crop Modelling.*

Rost, S., Gerten, D., Bondeau, A., Lucht, W., Rohwer, J., & Schaphoff, S. (2008). Agricultural green and blue water consumption and its influence on the global water system. *Water Resources Research*, *44*(9). https://doi.org/10.1029/2007WR006331

Schaldach, R., Alcamo, J., Koch, J., Kölking, C., Lapola, D. M., Schüngel, J., & Priess, J. A. (2011). An integrated approach to modelling land-use change on continental and global scales. *Environmental Modelling & Software*, *26*(8), 1041–1051. https://doi.org/10.1016/j.envsoft.2011.02.013

Schlesinger, M. E. (2007). *Human-induced climate change: An interdisciplinary assessment*. Cambridge University Press. https://www.cambridge.org/core/books/humaninduced-climate-change/83FB29EC151466A2E41634D0CF0A66A3 https://doi.org/10.1017/CBO9780511619472

Schlesinger, M. E., Kheshgi, H. S., Smith, J., La Chesnaye, F. C. de, Reilly, J. M., Wilson, T., & Kolstad, C. (Eds.). (2007). *Human-Induced Climate Change*. Cambridge University Press. https://doi.org/10.1017/CBO9780511619472

Schmitz, C., Biewald, A., Lotze-Campen, H., Popp, A., Dietrich, J. P., Bodirsky, B., Krause, M., & Weindl, I. (2012). Trading more food: Implications for land use, greenhouse gas emissions, and the food system. *Global Environmental Change*, *22*(1), 189–209. https://doi.org/10.1016/j.gloenvcha.2011.09.013

Schneider, C., Flörke, M., Eisner, S., & Voss, F. (2011). Large scale modelling of bankfull flow: An example for Europe. *Journal of Hydrology*, *408*(3-4), 235–245. https://doi.org/10.1016/j.jhydrol.2011.08.004

Schneider, C., Flörke, M., Stefano, L. de, & Petersen-Perlman, J. D. (2017). Hydrological threats to riparian wetlands of international importance – a global quantitative and qualitative analysis. *Hydrology and Earth System Sciences*, *21*(6), 2799–2815. https://doi.org/10.5194/hess-21-2799-2017

Schüngel, J., Stuch, B., Fohry, C., & Schaldach, R. (2021). Impacts of land cover initialization on globa land use simulations. *Environmental Modelling & Software*, submitted.

SE4All. Final SE4ALL AA Kenya January 2016[2].

Siebert, S., Henrich, V., Frenken, k., & Burke, J. (2018, August 1). *(PDF) Update of the digital global map of irrigation areas to version 5*. https://www.researchgate.net/publication/264556183_Update_of_the_digital_global_map_of_irrigation_areas_to_version_5

Siebert, S., Kummu, M., Porkka, M., Döll, P., Ramankutty, N., & Scanlon, B. R. (2015). A global data set of the extent of irrigated land from 1900 to 2005. *Hydrology and Earth System Sciences*, *19*(3), 1521–1545. https://doi.org/10.5194/hess-19-1521-2015

Siebert, S., Henrich, V., Frenken, K., & Burke, J. (2013). *Update of the Digital Global Map of Irrigation Areas to Version 5*. Rheinische Friedrich-Wilhelms-Universität, Bonn, Germany and FAO - Food and Agriculture Organization of the United Nations, Rome, Italy.

Sivapalan, M., TAKEUCHI, K., FRANKS, S. W., GUPTA, V. K., KARAMBIRI, H., LAKSHMI, V., LIANG, X., McDonnell, J. J., MENDIONDO, E. M., O'CONNELL, P. E., OKI, T., Pomeroy, J. W., SCHERTZER, D., Uhlenbrook, S., & Zehe, E. (2003). IAHS Decade on Predictions in Ungauged Basins (PUB), 2003–2012: Shaping an exciting future for the hydrological sciences. *Hydrological Sciences Journal*, *48*(6), 857–880. https://doi.org/10.1623/hysj.48.6.857.51421

Terrapon-Pfaff, J., Ortiz, W., Viebahn, P., Kynast, E., & Flörke, M. (2020). Water Demand Scenarios for Electricity Generation at the Global and Regional Levels. *Water*, *12*(9), 2482. https://doi.org/10.3390/w12092482

Turner, B. L., Lambin, E. F., & Reenberg, A. (2007). The emergence of land change science for global environmental change and sustainability. *Proceedings of the National Academy of Sciences of the United States of America*, *104*(52), 20666–20671. https://doi.org/10.1073/pnas.0704119104

van Asselen, S., & Verburg, P. H. (2013). Land cover change or land-use intensification: Simulating land system change with a global-scale land change model. *Global Change Biology*, *19*(12), 3648–3667.

van Soesbergen, A. (2016). *A review of land-use change models*. United Nations Environment Programme World Conservation Monitoring (UNEP-WCMC).

van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S. J., & Rose, S. K. (2011). The representative concentration pathways: An overview. *Climatic Change*, *109*(1-2), 5–31. https://doi.org/10.1007/s10584-011-0148-z

Verzano, K., Bärlund, I., Flörke, M., Lehner, B., Kynast, E., Voß, F., & Alcamo, J. (2012). Modeling variable river flow velocity on continental scale: Current situation and climate change impacts in Europe. *Journal of Hydrology*, *424-425*, 238–251. https://doi.org/10.1016/j.jhydrol.2012.01.005

Wagener, T., Wheater, H. S., & Gupta, H. V. (2004). *Rainfall-runoff modelling in gauged and ungauged catchments*. Imperial College Press. https://books.google.ne/books?id=hgtqDQAAQBAJ

Winemiller, K. O., McIntyre, P. B., Castello, L., Fluet-Chouinard, E., Giarrizzo, T., Nam, S., Baird, I. G., Darwall, W., Lujan, N. K., Harrison, I., Stiassny, M. L. J., Silvano, R. A. M., Fitzgerald, D. B., Pelicice, F. M., Agostinho, A. A., Gomes, L. C., Albert, J. S., Baran, E., Petrere, M., . . . Sáenz, L. (2016). Development AND ENVIRONMENT. Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong. *Science*, *351*(6269), 128–129. https://doi.org/10.1126/science.aac7082

Yu, Q., You, L., Wood-Sichra, U., Ru, Y., Joglekar, A. K. B., Fritz, S., Xiong, W., Lu, M., & Wu, W., and Yang, P. (2019). *Global Spatially-Disaggregated Crop Production Statistics Data for 2010 Version 2.0*. https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/PRFF8V

Zarfl, C., Berlekamp, J., He, F., Jähnig, S. C., Darwall, W., & Tockner, K. (2019). Future large hydropower dams impact global freshwater megafauna. *Scientific Reports*, *9*(1), 18531. https://doi.org/10.1038/s41598-019-54980-8

Zarfl, C., Lumsdon, A. E., Berlekamp, J., Tydecks, L., & Tockner, K. (2015). A global boom in hydropower dam construction. *Aquatic Sciences*, *77*(1), 161–170. https://doi.org/10.1007/s00027-014-0377-0

5 Outreach and Transferability

5.1 Environmental Sustainability Assessment (ESA)

Author: Alexander Lenz

Due to the composition of its set of indicators the environmental sustainability assessment (ESA) allows a direct comparison of the environmental impacts of the case studies of the WANDEL project. Furthermore, the underlying life cycle inventory shows in detail how the values come about, i.e. at which point in the construction and operation phase which impacts occur and what share they have in the overall impacts. In this context, the consideration of the upstream chains is of particular importance since many impacts with a strong environmental impact occur remotely (so-called remote impacts). The extent to which this is the case is presented and discussed in detail in Chapter 3.

5.1.1 Significance of the ESA for the EIA of energy plants

The ESA allows for a more comprehensive consideration of environmentally relevant impacts of energy systems than the traditional EIA. As already explained, off-site environmental impacts represent a very large proportion of the total amount of impacts. For example, in the course of the construction phase, not only the construction of the plant causes direct environmentally relevant impacts, but above all the resource extraction for and the production of the construction materials. This is the case for both fossil and renewable energy sources. During the operating phase, too, there are considerable environmentally relevant impacts away from the plant site. In particular this applies to electricity production based on fossil fuels, which depends on a permanent resource input. However, the present results show that energy production through the conversion of biomass into electricity and even CSP technology also depend on such input. The fact that the availability of this permanent resource input goes hand in hand with occasionally serious environmental impacts is a central point that the ESA, in contrast to the EIA, can identify and assess.

Furthermore, on the basis of the life cycle inventory the ESA is suitable for showing at which points in the upstream chain environmental impacts can be reduced or even avoided. This would be possible both during plant planning and retrospectively for existing energy production sites if the data were sufficiently concrete. To reduce environmental impacts, it is essential to make companies use material from those locations where their production is associated with less severe environmental impacts. Hence, they must be made subject to product liability by legislation or environmental damage has to be priced respectively. One example for how legislative acts may lead to closer looks on supply chains is the German supply chain law (“Lieferkettengesetz”). Starting in 2023, big companies must prove the origin of production materials and that, broadly speaking, human rights are respected within the supply chain. If they fail to prove the latter, they can be sanctioned.

Analogously to the visualised supply chain law, carrying out an ESA compels project sponsors to have a closer look on certain supply chains, with a focus on their ecological impacts. Following this approach, the individual LCA indicators can be used to identify most critical impacts. What is more, a higher use of building and operating materials from sites with lower environmental impacts puts economic pressure on those sites with higher impacts. In consequence this inevitably leads to impact reductions on the latter as they must remain competitive. This shows that, for example, the water scarcity footprint and the energy footprint – provided they are applied consistently and correctly – is a significant condition to achieve SDGs 6 and 7.

Therefore, the ESA proves to be a very useful and important addition to the conventional EIA or might even replace it. Above all this is true against the backdrop of increasing environmental and sustainability awareness, especially in the case of large-scale projects such as the power plants under consideration. In order to achieve the SDGs formulated by the UN, a comprehensive approach to the assessment of anthropogenic processes is indispensable. The ESA can be seen as a basis for this as it identifies both the indirect impacts occurring along the supply chain, whether they are remote or on-site, and the direct impacts *in situ*.

Another important aspect of projects such as energy plants which is considered in conventional EIAs and can be widely improved by using LCA methods are the impacts associated with the demolition or subsequent use of buildings and technical facilities after they have been abandoned. This aspect should be implemented in future ESA and will lead to detailed information if data is available in sufficient quality and quantity. For this purpose, not only the fate of the building materials obtained during demolition and the expenditure made for this, might be considered in LCA terms, but also the subsequent land use of the site and the natural flora and fauna that may become established after a certain period.

To prevent or reduce significant negative environmental impacts it is important to have detailed information on possible avoiding and compensatory measures as early as possible while planning a project. Such measures are an essential part of classic EIA and of great value for the protection of resources. They may either be specific project features that help to prevent or reduce significant negative environmental impacts or external measures with the same objective or aiming for impact compensation. The use of LCA methods enables the ESA to quantify exactly how much specific measures reduce or compensate the impacts of the project in planning.

5.1.2 Transferability to other regions and (energy) systems

The methodology used for the preparation of the ESA is designed to be able to examine and compare different processes at different locations. The unlimited transferability of this methodology to the diverse geographical regions of our planet and to other (energy) systems is primarily limited by the indicators and databases used.

For example, Koellner and Scholz (2007) point out that the Ecosystem Damage Potential indicator they developed, which serves as an indicator for the Land Footprint in this study, is based on biodiversity data from Central Europe and that an error-free application for other regions would require the implementation of further region-specific biodiversity values. This was not done in the present study for the two case studies outside Europe due to a lack of concrete biodiversity data. Although the effects of land use on biodiversity could vary greatly from region to region, Koellner and Scholz (2007) argue, that the indicator could be used as a reference method for other regions.

Against this background, the developed methodology for assessing the sustainability of anthropogenic processes and their upstream process chains is to be understood as such a reference method and not as a self-contained, unrestricted and immediately applicable tool.

Thus, the ESA is to be seen as an interface between the classical EIA and science-based sustainability indicators. The indicators used for the analysis of the case studies considered are designed to show a large part of the project-specific impacts in a comparable way. Some environmentally relevant aspects are left out of this analysis and must either be covered by other indicators or explained and evaluated verbally as it is done in this study, e.g., regarding the landscape as a protective good.

Anyway, the set of chosen indicators provides a comprehensive insight into the multifaceted environmental impacts of construction projects. Due to the common reference value of 1 kWh, the results are directly comparable. Processes that have the greatest impact during the construction and operation phase can be identified in the hotspot analysis. Applying ESA, the sustainability of energy production can be presented in a clear and transparent way.

5.1.3 Requirements for the applicability of the ESA in practice

The ESA is a suitable tool for assessing the sustainability of various processes. The use of extensive, already existing databases allows detailed conclusions to be drawn about construction- and operation-related impacts along the entire cause-effect chain. The incorporation of case-specific data into these databases and, in particular, the regionalisation of decisive resource flows allows precise statements about causal relationships. At the same time, a verbal-argumentative approach, as is common in conventional EIA, makes it possible to supplement information that the environmental indicators are not able to depict, or not in a suitable manner. To make ESAs applicable in practise there are several technical and methodological requirements that are outlined as follows:

1. There is a great need of detailed data and sometimes expensive databases about the specific project. These data may not only be descriptive but are required to be numeric in wide parts as they are supposed to be used in databases. Therefore, it is necessary that the project sponsor and other involved parties such as authorities provide detailed and comprehensive data.
2. Furthermore, it is evident that the improvement of existing indicators is indispensable for the use of ESA in practice. By way of example, the EDP indicator needs to be

adopted to further biogeographic regions, as mentioned above. Which indicators appear suitable for a high number of different projects and how they are to be used in detail needs further investigations.

3. As a result of this, there is a need for a precise definition of which indicators are to be used for future implementations of ESA. This definition must be worked out by scientists, policymakers and future ESA users together to ensure that the ESA can be implemented in the most efficient way giving the required outcome.
4. The EDP indicator proved to be useful to outline the impacts of occupation and transformation. This is especially true as the indicator is required to identify general remote impacts on ecosystems. Nevertheless, it is indispensable to assess the *in-situ* impacts on flora and fauna not only by indicators but by acquisition of data in the construction area, i.e., mapping of relevant species. This is the only way to identify any negative effects of planned projects on endangered species, local populations etc. Of course, this is not true for ESA being carried out in retrospect if such local data never has been acquired.
5. As pointed out in Chapter 2.1, the four case studies differ strongly in data availability, quality and quantity. One big advantage of the ESA, in contrast to the EIA, is, that there is a profound database in its background that is capable of compensating data scarcity to a certain point. This point is case study specific and depends strongly on the character of the project. Whether there is a need for a definition of minimum required data or not requires further research in terms of comparing different projects and analysing specific data requirements for the latter.
6. The results of an ESA widely depend on the used LCA database. Consequently, further improvements of such databases lead to better results of ESA implementations and should be further promoted in order to identify and name a project's most severe impacts both in solitary LCAs and in ESAs.

As shown above, on the one hand meeting the named requirements needs a great deal of scientific work. On the other hand, suitable policy frameworks are necessary. Legislature needs to work out for which kind of projects ESAs must be carried out. This may be done analogously to Appendix 1 of the current German environmental impact assessment law ("UVPG"), in which criteria are defined for projects requiring conventional EIAs. E.g., currently it is compulsory to carry out an EIA for the construction and operation of power plants with an electrical capacity above 200 MW. Hence, in the future such projects may require an ESA instead of an EIA. As a matter of course, such thresholds need to be defined for other types of large-scale projects, such as the construction and operation of dams, airports, factories etc.

5.2 Risk Analysis

Authors: Jazmin Campos Zeballos, Liliana Narvaez, Zita Sebesvari

Like any other industrial system, energy systems are exposed to natural hazards that could intensify due to climate change. Understanding the risk of a system to those hazards, identifying its strong and weak elements, and its negative and positive feedback loops within the system will help make decisions to increase resilience. Adaptation of renewable energy systems to climate change is necessary due to its increasing share in the global energy matrix and its key role to mitigate climate change.

The risk assessment undertaken in WANDEL is highly relevant for the global energy market since it enables to analyse the risk of biomass-based energy generation to droughts in the context of climate change. It provides a first-ever social-ecological-technological system analysis of a sugarcane-bagasse based electricity generation model. Transferable elements include the conceptualization of the social-ecological-technological system and the indicator-based risk assessment methodology. In the following, we describe the risk assessment methodology with respect to its transferability.

5.2.1 Aim of the risk assessments in the context of biomass-based electricity generation

Through a risk assessment, potential adverse impacts of, e.g. droughts exacerbated by climate change on a socio-ecological system can be identified (Reisinger et al., 2020). Risk assessments can help better plan the energy matrix and expansion considering both the water and energy-related SDGs and their achievements as well as the goals laid down in the National Adaptations Plans. Furthermore, it can shed light on the spatial distribution of exposed and vulnerable elements and thus helps to identify suitable areas for intervention to increase the system resilience under analysis.

5.2.2 Basis for the transfer

Although the methodology was applied in Brazil to sugarcane-based energy generation, the method can be applied globally after necessary adjustments.

The flexibility of risk assessment in its components gives the possibility to thoroughly analyse and assess a system considering social, environmental, and technological aspects.

Its components are designed to characterise levels of impact of natural hazards, identify exposed elements, and understand each subsystem's vulnerability. The data acquisition and the complexity of its further analysis will depend on the number of hazards analysed, the complexity of the energy system, and the data availability for a vulnerability analysis.

When data is available, the risk assessment will be a powerful tool to inform decision-makers about opportunities for improvement and risk reduction to increase resilience to future climate change and potential adverse impacts. However, if data availability is insufficient, the uncertainty of the analysis increases. Data for hazard analysis, and data for some exposure indicators, can be acquired by processing remote sensing data. However, data related to vulnerability, such as the quality of health services, existence and access to insurance for crops, is typically much localized and often lacking. Other social information, such as education level of the population, can be retrieved from national or governmental databases. Access to data – or lack thereof - on the energy generated by the plants' can also hinder the analysis, limiting the evaluation to assumptions about the plant design and sources used. Another factor to consider when doing risk assessments is that historical data might not always be available.

The system's delineation, the definition of their components, and geographic extension are crucial to have a meaningful analysis, which includes all the key elements as this is the basis for identifying the hazard or multiple hazards that the area is exposed to. Therefore, it will subsequently influence the definition of indicators and thresholds for the hazard characterisation.

The subsequent stakeholders' identification and involvement will depend on the characteristics of each subsystem. For water-related hazards, national and local authorities should be consulted to understand the whole system and to identify other relevant stakeholders for the system. Stakeholders will point to reliable data sources for hazard, exposure and vulnerability indicators.

The elements at risk are the exposed elements to include in each subsystem for the exposure assessment. Furthermore, the vulnerability assessment indicators will be built to understand the extent of the "*propensity or predisposition to be adversely affected*" of the exposed elements. A vulnerability assessment of energy systems will always include the social, ecological, and technological aspects.

5.3 Optimizing the Control of a Cascade of Hydropower Plants and Barrage Systems

Authors: Swantje Dettmann, Sarah Dickel, Tobias Vogtmann, Stephan Theobald

The optimization tool of the Eder and Diemel dams only needs a short computation time to simulate the discharge of the river system of approx. 405 km showing the effects of the operation of the dams on the river system. With the help of the optimizer integrated in RTC tools, the best optimal operation strategy can be determined for various management cases. Due to these features, the model can be used as a decision support system (DSS) for operating the Eder and Diemel dams, provided that forecast data is available. The optimization tool was handed over to the participating practice partner, the German Federal Institute of Hydrology (BfG), and can be used successfully to support decision-making.

The tools that were utilized or further developed for the cascade of hydropower plants on the Upper Danube make use of a one-dimensional hydrodynamic numerical (HN) model to model the hydraulic respectively hydrodynamic conditions within the 36 km long section of the Danube. The control algorithms installed on the real plants were copied into the simulation environment and coupled with the HN model which offered a wide range of investigations to be carried out about the impact of different management strategies on the hydraulic behaviour of the reservoirs as well as on further aspects such as - addressed in this study - the generation of electricity. Additionally, in cooperation with the company KIMA, the system was augmented and transformed into a user-friendly training tool be used by the staff of the practice partner.

Both the results from the case studies and the tools developed in the course of the project can be transferred to other river systems. In order to carry out the investigations described in Chapter 3 on the operation of a cascade of hydropower plants or the optimization of dam network systems for other river systems, HN models of the relevant sections must be created and integrated into the system as well as the regulatory structures and management rules. For a successful adaptation of these tools, advanced skills in using the modeling software are required. In addition, the system has to be calibrated using records of water level and discharge hydrographs prior to starting the examinations.

It is essential to understand the interdependencies in the modeled river system for the interpretation of the results. Because of their limited storage capacity, run-of-river hydropower plants only have a minor influence on the security of water availability, but they can help to reduce the effects of flood events if operated accordingly. When it comes to controlling storage dams, the short-term control analyzed in WANDEL always has to be evaluated and assessed in the context of year-round reservoir management as it is possible that the DSS meets all targets for a short period of time, but at the same time inhibits further support in the event of low water.

Both for the control of a cascade of hydropower plants as well as for the management of systems with multiple dams, the tools developed in WANDEL help the operating personnel for controlling the systems in real-time in the best possible way.

5.4 Governance Options

Author: Tobias Landwehr

5.4.1 Significance of the governance approaches

5.4.1.1 Energy-Water Security Assessment Set

There is no such thing as an ideal indicator set, not even for a single task or a prob-lem, as Arndt et al. (2006) noted. This is because each to-be-indicated issue obliges the context-based subjectivity of in-dicator selection. This also holds true for energy-water security, where there is a gap be-tween local and global analysis approaches that WANDEL seeks to close.

The IUSF research jumps in as a gap closer that not only links SDGs 6 and 7 within the Brundtland perspective, but also chooses the yet untouched regional scale for the indication. It hence serves as a bridge between national/global goals and local hands-on problems by assessing regional energy-water security.

A good example is the W4EF, which already tackles the energy-water correlation and is completely functional in its physical data-driven mindset. The approach deals with the en-ergy-water relation on a local scale (Lemoine and Bellet, 2015). However, it is unsuit-able for detecting structural problems, as certain aspects are not included at all, e.g. gov-ernance, competition or constraints on the water source (e.g. via droughts).

In contrast, however, stands the SDG reductionist approach. The SDGs disentangle global challenges into different targets and operate from an overarching macroscale that strengthens problem realization. However, ostensible SDG separation might lead to a cer-tain blindness or a simplification regarding interconnected issues (Zhang et al., 2016).

5.4.1.2 Stakeholder Imbalance Reduction (Morocco)

The IUSF research emphasizes the importance of pragmatic and participatory stakeholder inclusion in complex human-environment systems like the WEF-Nexus, especially in a local/regional context of the MENA region. Here, WANDEL held several workshops in the Middle-Drâa-Valley (MDV). In the last WANDEL workshop the gap between stakeholders – which was defined as the verto-horizontal disconnect – could be diminished via so called public action situation encounters, a methodology that joints normally separated stakeholder groups in joint problem analysis activities. This is a highly important step for strategy implementation as it creates a necessary common ground for WEF-challenge strategy application between stakeholders.

Post-Worskshop IUSF investigations demonstrated moreover via emergence analysis that pragmatic and participatory approaches were not very enrooted within the in the MDV stakeholders (and that they are most likely also not in MENA (Fayiah et al., 2020; Terrapon-Pfaff et al., 2018; Faysse et al., 2018)). The trust of both Public Profes-sionals (PPs) and citizens stakeholder in programs, organizations and politics that support pan-acea solution is still quite high. A similar observation of trust is made for rather top-down mid to grand scale solutions like reservoirs. The likelihood, that stakeholders are not aware of the panacea nature of programs, organizations and politics - that impedes the application of sustainable WEF-challenge strategies (Pahl-Wostl, 2015) and struc-tures like reservoirs is given and this would, indeed, endanger the application of long-term sustainable energy-water security strategies.

5.4.1.3 State of Water Basin Committees (Brazil)

Extensive expert interviews were carried out to receive an insight in the Goiás energy-water security administration and jurisdiction, with a focus on the important structure of water basin committees. The interviews delivered worthwhile insights that more often than not are not reflected in official reports.

As anticipated the interviews revealed that particularly important structures are Committees, which theoretically are quite strong and democratic. Government participation is limited to 40%, including the 3 spheres of government. The users have 60% of the votes of the Committee, divided between energy producers, farmers with farms of different sizes, and civil society through NGOs. The Committees are a council that recommends the policies to be taken in the basin in which they find themselves, counting on a way of self-financing that guarantees greater independence (Freitas et al., 2018; Ministério de Minas e Energia, Secretaria de Planejamento e Desenvolvimento Energático Departamen-to de Informações e Estudos Energéticos, 2020).

It is a promising and democratic tool but faces limitations with the internal cleavages be-ing significant, where many times we have impoverished farmers discussing with highly educated engineers of the powerful electric sector or big farming conglomerates and also financial imbalances, that make them unable to act. This holds especially true for areas in the sparsely settled area of the Centre-West (and thus Goiás).

The Committees are thus theoretically well-designed tools that face significant realization problems that compromise sustainability and security in the energy-water context by not guaranteeing necessary (ecologic, technical (e.g. surveillance of sedimentation at reservoirs) etc.) standards.

5.4.2 Transferability

Energy-Water Security Assessment Set

The IUSF research offers a new, holistic approach, based on a profound set of main and sub-indicators, for enabling different stakeholders to judge the regional security of water- dependent energy generation. The indicator system is a toolbox that allows the user to evaluate their local energy security based on carefully reasoned out criteria and definitions that are flexible enough to adapt to the manifold different situations that arise in regional energy generation. They can also be utilized individually for specific ques-tion only analysis, if a user so desires.

The set is designed independently for (sub) basin or administrative regions and thus suffers no restrictions regarding transferability. Practitioners on the whole globe might use it. Practitioners are administrations, NGOs, researchers or politicians, that seek a regional securi-ty elevation of their water dependent energy generation in the sustainable SDG context.

Stakeholder Imbalance Reduction

All in all, the IUSF research on strategy application to amend or overcome Water-Energy or Water-Energy-Food-Challenge sits into the observation of Pahl-Wostl (2019); Ostrom and

Cox (2010) that the nowadays prevailing panacea solution in governance are not apt to account for the highly localized complexity of WEF-Nexus problems and that indeed pragmatic and participatory contexts like public action situation encounters offer a promising perspective for sustainable solutions for local/regional WEF-challenges in the MENA.

The methodologies are easily transferable to other regional energy-water stakeholder imbalance settings, as the methodology is not bound to the specific context of the MDV. It is flexible, as the main prerequisite is former analysis of local stakeholder structure and their degree of interwoven action/communication.

State of Water Basin Committees

The theoretic concepts of the basin committee methodology would be easily transferable to quite every energy-water situation on the globe. However, as mentioned above, the real conditions often prevent the realization, so that committees cannot enact their full poten-tial. Analytical approaches like the expert interview applied by the IUSF reveal such situa-tions. Based on the findings, improvements might be initiated like the Brazilian national water agency (ANA) tries with their Progestão e Procomitê, programs that seek to address this difference at the federal and state levels of water resources management and resolve the internal difference between committee participants, which was, however, initiated in-dependently of the WANDEL research findings.

5.4.3 The results in practice

The methodologies presented in the research offer methodological baselines that suffer little restriction of application by data or resources. The assessment set is based upon al-ready existent data sources that are either based on published and continued research or administrative, but not overly complex base data (i.e. population data). In case of missing data, the assessment set is easily adjustable via omission of certain sub-indicators, which is reflected in its rating. The other two methodologies (expert interviews and public action situation encounters) are theoretic approaches, which are quite straightforward and not lim-ited by resources.

The methodology of the research is thus easily reproducible with sufficient human resources, i.e. a small one- or two-digit researcher group. It is moreover recommended to enhance the research to other regions of the globe to reveal, whether stakeholder imbalances or the lack of realization of good administration concepts like committees is a general issue in the energy-water security context, that ought to be fixed. The presented assessment tool, the public action situation encounters or methodologies pointed out by the expert inter-views in Goiás are worthwhile approaches to identify in how far energy security is restrict-ed or even endangered by (mismanaged) water supply.

5.5 References Chapter 5

Arndt, C., & Oman, C. (2006). *Uses and abuses of governance indicators*. *Development Centre studies*. Development Centre of the Organisation for Economic Co-operation and Development.

Fayiah, M., Dong, S., Singh, S., & Kwaku, E. A. (2020). A review of water–energy nexus trend, methods, challenges and future prospects. *International Journal of Energy and Water Resources*, *4*(1), 91–107. https://doi.org/10.1007/s42108-020-00057-6

Faysse, N., Sellika, I. E., Rinaudo, J.-D., & Errahj, M. (2018). Participatory scenario planning for sustainable irrigated agriculture when actors seldom communicate: an experiment in Morocco. *International Journal of Water Resources Development*, *34*(6), 982–1000. https://doi.org/10.1080/07900627.2017.1322500

(2018, June). Interview by M.d.S. Freitas, & Landwehr, T., Campos J.

Koellner, T., & Scholz, R. W. (2008). Assessment of land use impacts on the natural environment. *The International Journal of Life Cycle Assessment*, *13*(1), 32–48. https://doi.org/10.1065/lca2006.12.292.2

Lemoine, Y., & Bellet, L. (2015). *Water for energy framework - evaluation of the local interactions between energy sites and water - general report.*

Ministério de Minas e Energia, Secretaria de Planejamento e Desenvolvimento Energático Departamento de Informações e Estudos Energéticos. (2020). *Resenha energética brasileira: 2020.*

OSTROM, E., & COX, M. (2010). Moving beyond panaceas: a multi-tiered diagnostic approach for social-ecological analysis. *Environmental Conservation*, *37*(4), 451–463. https://doi.org/10.1017/S0376892910000834

Pahl-Wostl, C. (2019). Governance of the water-energy-food security nexus: A multi-level coordination challenge. *Environmental Science & Policy*, *92*, 356–367. https://doi.org/10.1016/j.envsci.2017.07.017

Pradhan, P., Costa, L., Rybski, D., Lucht, W., & Kropp, J. P. (2017). A Systematic Study of Sustainable Development Goal (SDG) Interactions. *Earth's Future*, *5*(11), 1169–1179. https://doi.org/10.1002/2017EF000632

Terrapon-Pfaff, J., Ortiz, W., Dienst, C., & Gröne, M.-C. (2018). Energising the WEF nexus to enhance sustainable development at local level. *Journal of Environmental Management*, *223*, 409–416. https://doi.org/10.1016/j.jenvman.2018.06.037

Zhang, Q., Prouty, C., Zimmerman, J. B., & Mihelcic, J. R. (2016). More than Target 6.3: A Systems Approach to Rethinking Sustainable Development Goals in a Resource-Scarce World. *Engineering*, *2*(4), 481–489. https://doi.org/10.1016/J.ENG.2016.04.010

6 Key Findings and Policy Relevant Recommendations

This chapter summarizes the key findings of the WANDEL project. Based on our experiences from the project, we have derived policy relevant recommendations that are particularly directed to actors involved in water management and energy transition planning. The insights that we have gained in WANDEL convinced us that actors from public authorities, companies, civil society organizations, NGOs, international development organizations, and research can benefit from our findings. Findings that help to prevent trade-offs between SDG 6 and SDG 7 and to achieve synergies.

6.1 Key Findings from the global scale

- We show that the future structure of the power supply and thus the future water demand for power generation are subject to high levels of uncertainty. This is due to the fact that water withdrawal and consumption intensities of electricity generation vary significantly depending on the choices made in the coming years regarding power generation technologies and cooling systems.
- Our results show that ambitious decarbonization scenarios involving wide-scale deployments of renewables and a high electrification rate of the end use achieve the lowest water intensities. However, in combination with inefficient power plant and cooling technologies these strategies in absolute terms, could consume more water than less ambitious decarbonisation scenarios.
- The Environmental Sustainability Assessment (ESA) allows for a more comprehensive consideration of environmentally relevant impacts of energy systems than the traditional Environmental Impact Assessment (EIA) due to more detailed analysis of upstream supply chains.
- Strategies for reducing the water scarcity footprint and the energy footprint are essential for achieving SDGs 6 and 7. These indicators support the identification of (adverse) opposite influences.

6.2 Key Findings from the Case Studies

- Simulation tools are important to identify trade-offs between hydroelectricity generation and water resources. Further developments supported the optimisation of technological measures to control the operation of a cascade of six hydropower plants at the Upper Danube by implementing an onsite training simulator to efficiently practice personnel.

- Simulation-based optimization of the reservoir management at the Eder and Diemel dams (both located in the Weser river basin) supports the identification of measures for an adapted management of available water resources. In the context of short-term management, the tool allows for quantity- and time-adjusted releases of water resources from the storages. However, it turned out that dam releases to raise water levels during prolonged dry periods are hardly practicable.
- Hydroelectricity generation can be increased by increasing the target water level, and with smoothed discharge levels there is less wear on the construction with unchanged total power generation.
- The drought risk assessment results of Rio dos Patos basin showed the importance of the protection of key areas (for example riparian areas) to reduce drought risk and drought impacts as well as the need for a platform to monitor the protected areas in order reduce the overall risk for the environment. Protected areas reduce the vulnerability of the region to water related hazards, while the monitoring increases the awareness of farmers for the importance of these areas.
- Access to weather forecast and information about soil moisture was found important to reduce the drought risk of sugarcane production; however, an early warning is still missing in the sector and it contributes to the vulnerability of the system.
- Farmers, sugar mill managers, and researchers are aware of the impacts of climate change and drought events. Farmers are willing to provide monetary contribution or land to build small dams and water storage for the dry season and they believe that these are a crucial adaptation mechanism of the sugarcane system to climate change and a likely increase in the frequency of drought events.
- The case study for Morocco shows that water supply and demand developments prove to be the most critical components in the analysed water-energy-agriculture nexus setting, with water ultimately becoming the limiting factor for all other sectors.
- The scenarios developed in conjunction with the local stakeholders for the case study region in Ouarzazate Morocco show that the extent and frequency of unmet water demand will depend on social and economic developments. But even with major changes towards sustainable water use in the Middle Drâa Valley, the energy and agricultural sectors - and consequently local livelihoods - are likely to be negatively affected by the diminishing water supply.
- With few exceptions, the impacts of energy systems identified using Life Cycle Analysis (LCA) indicators point to remote impacts on the environment, especially on water resources. Nevertheless, significant environmental on-site impacts often cannot be identified using LCA indicators at case study level but descriptive methods.
- In this context, the ESA is universally applicable in different geographical regions and transferable to other (energy) systems. However, it must be pointed out that the underlying indicators require numerous input data, some of which are only commercially available.

6.3 Policy relevant recommendations

- To achieve the SDGs as set up by the United Nations, a comprehensive approach to assess anthropogenic impacts is indispensable and needs to be implemented mandatorily. Spatially explicit analyses reveal hotspots of environmental impacts along the case study supply chains. We conclude that a spatially explicit environmental assessment of upstream supply is a suitable tool to identify and evaluate teleconnections, and hence, should be considered when designing energy supply concepts and infrastructures to avoid problem shifting.
- Reducing greenhouse gas emissions (GHG) from electricity generation does not necessarily lead to a reduction in water demand. Energy transition strategies should therefore consider not only the potential to reduce GHG, but also other environmental dimension such as the water demand and impacts on biodiversity of the future energy system.
- Long-term energy scenarios are required that fully consider the impacts on water resources and biodiversity onsite and remotely of the modelled (planned) energy system. In order to address future energy generation (SDG 7), the common optimization with regard to climate targets (SDG 13) should be extended to cover water quantity and quality targets (SDG 6) as well as biodiversity and ecosystem health (SDG 14 and 15). This in turn raises methodological questions regarding a multi-target optimization problem.
- To reduce environmental impacts, it is essential to make companies use material and resources from those locations where production is associated with less severe environmental impacts. In order to achieve this goal, product liability should therefore be imposed by law, or environmental damage should be priced.
- Available water resources and different technological options for both power plants and cooling systems should be explicitly considered when designing and evaluating future electricity systems. Incentives to improve the water use and power generation can help to increase the amount of electricity that can be injected into the grid during the dry season and drought events.
- The impact of climate change on water resources needs to be considered in order to derive (optimized) operational requirements of conventional and renewable power generation. Further research on the effects of long drought events for power generation in combination with the severe ecological and socio-cultural implications should be conducted.
- A targeted, optimised reservoir release can effectively realise the operational requirements for hydropower generation so that the use of the available water resources is optimised. Against the background of climate change, the adjustment of long-term operational requirements can support conserving water for the achievement of short-term goals.
- Cascades of run-of-river power plants are suitable for providing operating reserves and can thus contribute to achieve (green) energy and water security. The development and use of a training simulator and optimisation tool to control river discharge are valuable technical aids to practice the operating staff, particularly in case of critical discharge situations.

- The focus of discussions and applications of the water-energy nexus has mainly been at national or global levels. For an improved understanding of the interlinkages and potential conflicts between energy and water more studies are needed that analyse the water-energy nexus at the local level. Here, the assessment of the water-energy nexus also should include participation of multiple actors to allow for comprehensive analyses that consider resources and human dimensions of the nexus. This will not only help to avoid competition for water resources between sectors but develop strategies for synergies.
- Farmers and sugar mill owners are well organised, and have been working to improve the sector´s water use efficiency. Currently better infrastructure (technology used in the mills) and access to small dams are key to reduce the drought risk of the sector. Proactive government involvement and a plan to identify spots where small dams can be built can help to better plan water allocations and storage in the region avoiding jeopardising the ecological flow of the river.
- There is still a need to bridge science with policy. Research is key to reduce onsite and remote impacts on water resources due to electricity production based on conventional and renewable energy systems. During the project it became clear that the research and institutional lines and actions in the energy sector were mostly planned without agreement with institutions from the water sector (or others) and sometimes were not aware of the research undergoing in the sector.

List of Figures

List of Tables

Abbreviations

Allgemein

AFR	Sub-Sahara Africa
AMDi	Water Availability-Minus-Demand on grid cell level
ANA	Brazilian national water agency
API	Application Programming Interface
AWARE	Available WAter REmaining
BfG	German Federal Institute of Hydrology
C_2H_6	Ethane
CCI	Climate Change Initiative
CED	Cumulative energy demand
$CED_{fo/re}$	Cumulative energy demand (fossil/renewable)
CH_4	Methane
$CHCl_3$	Chloroform
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CPA	Centrally Planned Asia
CPI	Concentration Precipitation Index
CSP	Concentrated solar power
DEM	Digital Elevation Model
DIF	Demand increase factor
DMS	Document Management System
DPSIR	Drivers-Pressures-State-Impact-Response
DSS	Decision Support System
ECO	Ecosystem Quality
EDP	Ecosystem Damage Potential

EIA	Environmental Impact Assessment
EROI	Energy Return on Investment
ESA	Environmental Sustainability Assessment
EU	European Union
EUR	Europe (incl. Turkey)
FAO	Food and Agriculture Organization of the United Nations
FAOSTAT	Food and Agriculture Organization Corporate Statistical Database
FOSS	Free and Open Source Software
FSU	Former Soviet Union
GAEZ	Global Agro-Ecological Zone
GMIA	Digital Global Map of Irrigation Areas
GWP	Global Warming Potential
GWP100	Global Warming Potential (100 yr time frame)
HN model	Hydrodynamic Numerical model
HuHe	Human Health
IPOPT	Interior Point Optimiser
ISO	International Organization for Standardization
LAM	Latin America
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LULC	
MCA	Multi-criteria Analysis
MDV	Middle-Drâa-Valley
MEA	Middle East and North Africa
MENA	Middle-East-North-Africa
MLK	Mittelland Canal
MPC	Model predictive tool
NAM	North America
OECD	Organisation for Economic Co-operation and Development

OGC	Open Geospatial Consortium
PAO	Pacific OECD
PAS	Pacific Asia
PDSI	Palmer Drought Severity Index
PMF	Product Material Footprint
RTC	Real-Time Calculus Toolbox
RMI	Raw Material Input
SAS	South Asia
SDG	Sustainable Development Goal
SDI	Spatial Data Infrastructure
SET	Social-Ecological-Technological
SF_6	Sulfur Hexafluoride
SOS	Safe-Operating-Space
SPEI	Standardised Precipitation-Evapotranspiration Index
SPI	Standard Precipitation Index
SSP	Shared Socio-Economic Pathway
TMR	Total Material Requirement
UVPG	German Law on Environmental Impact Assessment
VM	Virtual machine
W3C	World Wide Web Consortium
W4EF	Water for Energy Framework
WEF-nexus	Water-Energy-Food nexus
WF	Water Footprint
WHO	World Health Organisation
WMS	Web Mapping Service
WSF	Water Scarcity Footprint
WSF_{qual}	Qualitative Water Scarcity Footprint
WSF_{quan}	Quantitative Water Scarcity Footprint

Annexes

List of Annexes:

Annex A	Supplementary Material Chapter 2.2 - Description of the LCA models of the case studies
Annex B	Supplementary Material Chapter 4.2 - Land Use change Scenarios - detailed modeling approach

Annex A: Supplementary Material Chapter 2.2

The following section will be published by Schomberg et al. 2021 [submitted]. Further details, in particular a data availability statement, can be found there. Information without direct reference have been kindly provided by the operators in their function as practice partners in the project WANDEL.

The LCA models of the four case studies are described below, consisting of general information, modifications of the used ecoinvent 3.5 dataset (Wernet et al. 2016) for the construction and operation phases, a definition of the functional unit, and the allocation approach and information on specific data handling.

Case study 1, the coal-fired power plant Heyden in Petershagen on the Weser River, was chosen as reference for conventional power generation within the project WANDEL. It is still the most powerful power plant in Germany with a net capacity of 875 MW, although commissioned already in 1987. In connection with the German coal phase-out it is expected to remain in operation until the end of 2025. The fuel used is hard coal, which is mainly supplied from Russia. The exhaust gases from combustion are cleaned by gradually passing through denitrification, dedusting and desulfurization plants. Wastewater is treated by one of the world's first ultrafiltration plants. The coal power plant produces other reference products such as fly ash, gypsum and slag during the operational phase, which are reused for various purposes, but neglected here for their small economic value. For the case study modelling, an ecoinvent 3.5 dataset for an average European coal-fired power plant is used and no modifications are made for the construction phase. For the operational phase, the net water demand is assumed to be 0.001 m^3 kWh^{-1}. This value is obtained by considering the loss from cooling water input. Moreover, a variety of material inputs and emissions to air and water, such as cadmium and mercury, are added. The functional unit of the operational phase is 1 kWh for all case studies. The construction phase inventory is also related to 1 kWh by a factor resulting from a total electricity production of 10^{11} kWh over a lifetime of 35 years considering the German coal phase-out and a capacity of 875 MW.

Case study 2, the hydropower plants on the Danube, consists of six barrages between the Bavarian towns of Oberelchingen and Faimingen which were built between 1960 and 1965. They have two double-regulated Kaplan turbines with standing shafts and one directly attached synchronous generator each. The heads are 5 to 7 m, the outputs are 7 to 10 MW, and each weir generates an average of about 50 GWh per year. An ecoinvent 3.5 dataset for an average European ROR hydropower plant is used as the basis for the case study modelling. For the construction phase, areas transformed during construction or occupied by case study facilities are analysed from satellite imagery. For the other case studies, this has been carried out analogously. For the operational phase, the equation P = Q x h x c1 is used to calculate a turbine water consumption of 111 m^3 kWh^{-1} (P: power in W, Q: water flow in m^3 s^{-1}, h: head in m, c1 = 8.5 KN m^{-3}, where the latter includes gravity, density of water and a plant efficiency of 85%). As additional impoundment areas are responsible for additional evaporation losses during the operational phase, this is considered by taking into consideration a total conversion to water bodies by the six impoundments of about 1 million m^2 and an evaporation rate of 643 L m^{-2} a^{-1}, as described in the literature for similar latitudes (Berry & Stichling 1954). Evaporation losses from impoundment are hence calculated as 0.02 m^3 kWh^{-1}, as the reservoir water evaporation of 0.03 m^3 kWh^{-1} used in ecoinvent 3.5 for German non-alpine reservoirs could not be verified. The measurement of additional impoundment areas was carried out with the help of satellite images and is subject to a great deal of uncertainty. In the absence of more precise data, they are intended to give an idea of the possible magnitude of water consumption through evaporation. Due to their spatial proximity, the six impoundments were accounted for together as one case study. The construction phase inventory is referenced to 1 kWh by a factor based on the total power of the six dams of 52 MW, an annual production of 50 million kWh, and a lifetime of 80 years (Dones et al. 2007) for the cement in dams, tunnels, and control units (the latter considered only in the conversion for the construction phase). Shorter lifetimes for steel and pipes are already considered in ecoinvent 3.5.

Case study 3, the Noor I CSP, commissioned in 2016, is located near the city of Ouarzazate. The site has one of the highest solar irradiances in the world, with 2,635 kWh m^{-2} annually. The plant comprises a solar field, a power block and a thermal energy storage unit. It has a capacity of 160 MW. In the solar field, parabolic trough collectors use solar radiation to heat a heat transfer fluid. The power block, consisting of a steam generation system, superheater, turbine, reheater, condenser, preheater, optional boiler, heat exchangers, cooling tower, and pumps, takes this fluid to convert it into electricity (Aquachmar et al. 2019). Unlike Noor's successor projects in the region, Noor I's cooling system still relies on water. Additionally, water is needed to remove sand from the solar panels. It is drawn from the nearby El Mansour Eddahbi reservoir. An ecoinvent 3.5 dataset for a 50 MW CSP is used as the basis for the case study modelling. For the construction phase, an occupancy of about 40 million m^2 by industrial areas and a total water consumption of 0.3 million m^3 are considered. For the operation phase, the energy input from the sun is accounted for. It is calculated by dividing the energy output of 1 kWh by 25% representing the thermal energy-to-electricity-efficiency (Piemonte et al. 2012). For the LCA analysis, the total energy input is not considered, but the efficiency of the system after the solar heat is converted into thermal energy. If the solar energy to thermal energy conversion efficiency of about 59% (Piemonte et al. 2012) is considered, the total solar energy-to-electricity-efficiency would be 15% (Soomro et al. 2019). A water consumption of about 5 l kWh^{-1} is considered for cooling purposes and cleaning of solar panels as evaporative loss. The construction phase inventory is referenced to 1 kWh using a factor based on the total capacity of 160 MW, a net annual production of 370 million kWh (data kindly provided by the operator), and a lifetime of 30 years (Raboaca et al. 2019, considered only in the conversion for the construction phase).

Case study 4 is the sugarcane cultivation in the Rio dos Patos basin, Brazil. Sugarcane is grown on a total available area of 65,000 ha of formerly degraded pasture land. After harvest the fresh plants are crushed to separate the plant fibres from the sugar cane water. The fibres are further processed to produce sugar, ethanol and yeast. The remaining sugar cane water, known as venasse, is returned to the fields as irrigation water and fertilizer to complete the cycle. The squeezed plant fibres, known as bagasse, are burned through a system of boilers, steam turbine and generator to produce electricity. The electricity is partially used for self-supply and otherwise fed into the power grid, while additional heat generated is fed into the sugar fermentation process. Since 54% of the sugar cane produced each year is irrigated and water shortages can often occur in the region during the dry season, the operator is making extensive efforts to steadily reduce water consumption in agriculture and industry (see also chapter 3.4.1). Two LCA models with different system boundaries were chosen for the analysis of the case study, which differ in that (1) bagasse is considered as a reference product of sugar and ethanol production and (2) as their waste product. From an LCA perspective, this is a critical issue which is described in detail by Schomberg et al. 2021 (in preparation). In order to be able to do justice to the different circumstances, especially in international comparisons, both models were considered comparatively in this study. The model with bagasse as reference product is based on a dataset from ecoinvent 3.5 for electricity from sugarcane (Jungbluth & Chudacoff 2007). For the construction phase, a 40 MW gas turbine and a conversion of approximately 500,000 m^2 of pasture to industrial land were added. For the operation phase, in the sugarcane production process step, the calorific value of sugarcane of 5 MJ kg^{-1}, the conversion of pasture to irrigated and non-irrigated annuals, the occupancy of irrigated and non-irrigated annuals, and an evapotranspiration of 0.38 m^3 kg^{-1} were considered. In the power generation process step, a net water demand of 0.008 m3 kWh^{-1} was considered due to evapotranspiration losses from the boiler system. For the bagasse as reference product, an economic allocation of sugarcane juice and sugarcane bagasse was carried out. The LCA waste model is based on the same ecoinvent 3.5 data. For the construction phase, only the 40 MW gas turbine was considered without modifications. For the operation phase, only the power generation process step was considered with a net water demand of 0.008 m^3 kWh^{-1}. The construction phase inventory was referenced to 1 kWh using a factor based on a net annual bagasse production of 700 million kg, a turbine capacity of 40 MW, a service life of 50 years and an estimated share of bagasse processing infrastructure in the total sugar mill of 5%.

References Annex A

Aqachmar, Z., Allouhi, A., Jamil, A., Gagouch, B. & Kousksou, T. (2019). Parabolic trough solar thermal power plant Noor I in Morocco. *Energy* **178**, 572–584

Berry, W. M. & Stichling, W. (1954). Evaporation from lakes and reservoirs in the northern plains region of North Dakota. in *IUGG General Assembly*

Dones, R. *et al.* (2007). Swiss Centre for Life Cycle Inventories A joint initiative of the ETH domain and Swiss Federal Offices Life Cycle Inventories of Energy Systems: Results for Current Systems in Switzerland and other UCTE Countries Data v2.0 (2007) Villigen and Uster.

Jungbluth, N. & Chudacoff, M. (2007). Life cycle inventories of bioenergy. *Final report ecoinvent*, pp143-157 (2007).

Piemonte, V., Falco, M. De, Tarquini, P. & Giaconia, A. Life Cycle Assessment of a high temperature molten salt concentrated solar power plant. *Sol. Energy* **85**, 1101–1108 (2011).

Raboaca, M. S. *et al.* (2011). Concentrating solar power technologies. *Energies* **12**, (2019).

Soomro, M. I. *et al.* (2019). Performance and economic analysis of concentrated solar power generation for Pakistan. *Processes* **7**, 1–25 (2019).

Wernet, G. *et al.* (2016). The ecoinvent database version 3 (part I): overview and methodology. *Int. J. Life Cycle Assess.* **21**, 1218–1230 (2016).

Annex B: Supplementary Material Chapter 4.2

Land Use change Scenarios - detailed modeling approach

For the simulation of the spatial distribution of irrigated cropland, basically the same input data is used as for rainfed cropland as both apply for farming activities in general. However, to allocate irrigated cropland areas separately from cropland areas under rainfed conditions, additional irrigation specific input data is needed. An overview of model input data is given by Table B 1. Information on the current location and extent of irrigated areas is taken from the dataset of the Digital Global Map of Irrigation Areas (GMIA) (Siebert et al., 2013). It provides global information on the area equipped for irrigation per grid cell around the year 2005 with a spatial resolution of 5 by 5 arc-minutes. Information on the harvested area as well as the produced amount of different crop types per country is taken from FAOSTAT (FAO, 2021b) for the initial land use map and from scenario assumptions for simulation runs. Since data from FAOSTAT do not differentiate between irrigated and rainfed conditions, results from the SPAM model (IFPRI, 2019) are used and aggregated at country level to split FAOSTAT data into irrigated and rainfed parts. SPAM[1] disaggregates crop statistics and produces global gridded maps of agricultural production patterns at a 5 arc-minute spatial resolution for 42 crops and four farming systems. Information on potential crop yields per grid cell is generated by the dynamic global vegetation model LPJmL[2] (Bondeau et al., 2007), under both rainfed as well as irrigated conditions. Data are provided on a global grid with a 30 arc-minute resolution for current climate conditions (averaged over the reference period 1971–2000). Since irrigation needs water, the accessibility to water is a crucial factor for irrigation farming. This information is derived by calculating a river network density per grid cell as a line density of streams per grid cell based on A Simple Global River Bankfull Width & Depth Database (Andreadis et al., 2013). In order to decide where and to what extend irrigated cropland areas are allowed to expand, so-called irrigation units are formed, which represent a reference space (see below). First and most important reference space is formed by 143,653 river basins and sub-basins provided by the global water model WaterGAP3, covering the global land area except Greenland and Antarctica (Brauman et al., 2016; Eisner, 2016). If a river basin does not meet the requirements as a reference space, larger spaces formed by country borders and 18 Global Agro-Ecological Zones (GAEZ) are used. Each GAEZ is characterized by similar growing conditions considering length of

[1] SPAM website: https://www.mapspam.info/

[2] LPJmL website: https://www.pik-potsdam.de/en/institute/departments/activities/biosphere-water-modelling/lpjml

growing period, absolute minimum temperature and growing degree days (Ramankutty et al., 2007).

In order to identify grid cells that have appropriate conditions and thus a high probability of a particular land use, the preference of each grid cell is identified at the beginning of every time step based on micro level information. Then a ranking list of evaluated grid cells is generated, starting with the highest preference value. A full description of the general procedure is given in (Schaldach et al., 2011) and (Schüngel et al., 2021). The preference of each grid cell arises from a multi-criteria analysis considering suitability factors and constraining factors. Suitability factors comprise the most relevant geographical as well as biophysical conditions. Constraining factors will allow certain land use changes to be prohibited if minimum requirements are not met. Examples are land use changes within a nature conservation area may be prohibited by policy decisions or the assumption of a minimum potential yield per hectare to be converted to cropland. To calculate the suitability of a grid cell for irrigated crop types, basically the same factors are used as for rainfed crop types. Additional irrigation specific factors are potential irrigated crop yield and river network density. Potential irrigated crop yield is an indicator of productivity with high values indicating a high suitability. River network density provides information on the accessibility to surface water resources. Again, a positive correlation is assumed between the factor and the grid cells' suitability. Irrigation specific constraint factors are minimum irrigated yield and minimum yield gain. The minimum yield gain ensures that the higher effort of irrigation farming provides an adequate advantage over rainfed farming. It describes a defined minimum difference between the crop type specific potential irrigated and rainfed yield per grid cell that has to be exceeded to allocate the respective irrigated crop type. In addition to the minimum yield gain, a minimum irrigated yield is used to define the minimum productivity from which it is worthwhile to cultivate an irrigated crop on a grid cell, regardless of the yield difference between irrigated and rainfed conditions. Table B 2 gives an overview of all suitability and constraint factors used for calculating a grid cells' preference for irrigated crop types.

LandSHIFT is always initialized with a global land cover map based on remote sensing, which provides information on the location of settlement and cropland as well as a variety of natural land cover types such as forest, grassland and shrubland. For this study we used CCI land cover map for the year 2015 (ESA Climate Change Initiative, 2017). As we consider GMIA as the current state of global irrigated areas, irrigated crop types are initially allocated only to areas given by this database, according to the demand derived from the statistical data from FAOSTAT as well as the SPAM model. The result is a global map showing the current crop type specific distribution of irrigated crop land. It builds the base map for the following scenario simulation runs. The model distinguishes between 11 primary crop classes, each under irrigated and rainfed conditions. These are: temperate cereals, tropical cereals, maize, annual oil crops, pulses, rice, temperate roots and tubers, cotton, soybean, sugarcane, other crops. In addition, fodder crops are modelled only under rainfed conditions. Usually, the irrigated area given by GMIA or the previous time step does not perfectly match the demand from the statistics or scenario data. In case that not all given area is needed to meet the demand, areas of less suitable grid cells are not used and turn into the land use type set-aside_irrigated. It is subjected for possible re-use by irrigated crop types for several time steps and cannot be replaced by rainfed crops or pasture. According to cost-benefit strategies, it is assumed that reactivating former used irrigation infrastructure is more likely than installing new irrigation systems and developing new irrigated cropland. In case that more area is needed than given by GMIA or the previous time step, at first the set-aside_irrigated areas are used, if existent (only possible in simulation runs). If set-aside_irrigated does not exist or is insufficient, additional new suitable land has to be converted to irrigated cropland that has never been irrigated before.

The extent of expansion of new irrigated area of a suitable grid cell is based on statistical values (see below) of all irrigated grid cells located within the same irrigation unit. An irrigation unit is a reference space and basically formed by one out of 143,653 river (sub) basins. In order to calculate robust statistics, a river (sub) basin has to meet two minimum requirements. It must have a size of at least 100 grid cells and at least 10 irrigated grid cells. If this is not the case, lager reference spaces are needed such as countries or GAEZs. At first statistics are calculated based on all irrigated grid cells located within the same country as well as the same GAEZ. If this is not sufficient (< 100 grid cells, < 10 irrigated grid cells), statistics are calculated based on all irrigated grid cells within the same country. If this is still not sufficient, only the GAEZ forms the irrigation unit. And in the rare case that this is still not sufficient, a global default value is used. The overlay of countries and GAEZ is a proper substitute since it considers the socio-economic conditions of a country as well as its possible variety of natural growing conditions. This accounts especially for large countries. Two statistical values, the median and the 90th percentile, are calculated from the fractions of irrigated area of each irrigated grid cell within the same irrigation unit. For the initial base map these values are calculated after all areas given by GMIA have been fully utilized. For the scenario simulation runs they are calculated at the beginning of every time step based on the final irrigated areas of the previous time step. Hence, they change and adapt with every time step, provided that there was a change in irrigated area in at least one grid cell. If the irrigated fraction of area within a suitable grid cell is lower than the median value of all irrigated grid cells within the same irrigation unit, the irrigated fraction of the grid cell is expanded to the median value. If the irrigated fraction of a suitable grid cell is already higher or equal to the median value of all irrigated grid cells within the same irrigation unit, the fraction of the grid cell is expanded to the 90th percentile. The 90th percentile value ensures that possible outliers do not distort the result (in contrast to a maximum value). In case that the irrigated fraction of a grid cell is already above the 90th percentile value, it is expanded (limited to grid cells' total available land area) according to the demand increase factor (DIF). DIF describes the relative change in demand for an irrigated crop type per country compared to the demand of the previous time step. If after this procedure demand is left, the procedure is repeated once again, but without considering the median value, since all suitable cells have already expanded their irrigated area at least up to the median value. If this was still not sufficient, grid cells are allowed to expand the irrigated area up to cells' maximum available land area. The allocation of irrigated crop types ends when all demand is met or nor more land is available. In the latter case, the left over is saved in a text file. Figure B 1 depicts the first round of the algorithm for allocating irrigated crop production to new irrigated areas, i.e. the first round after all already existing irrigated areas as well as set-aside_irrigated areas have been fully utilized and expansion is required.

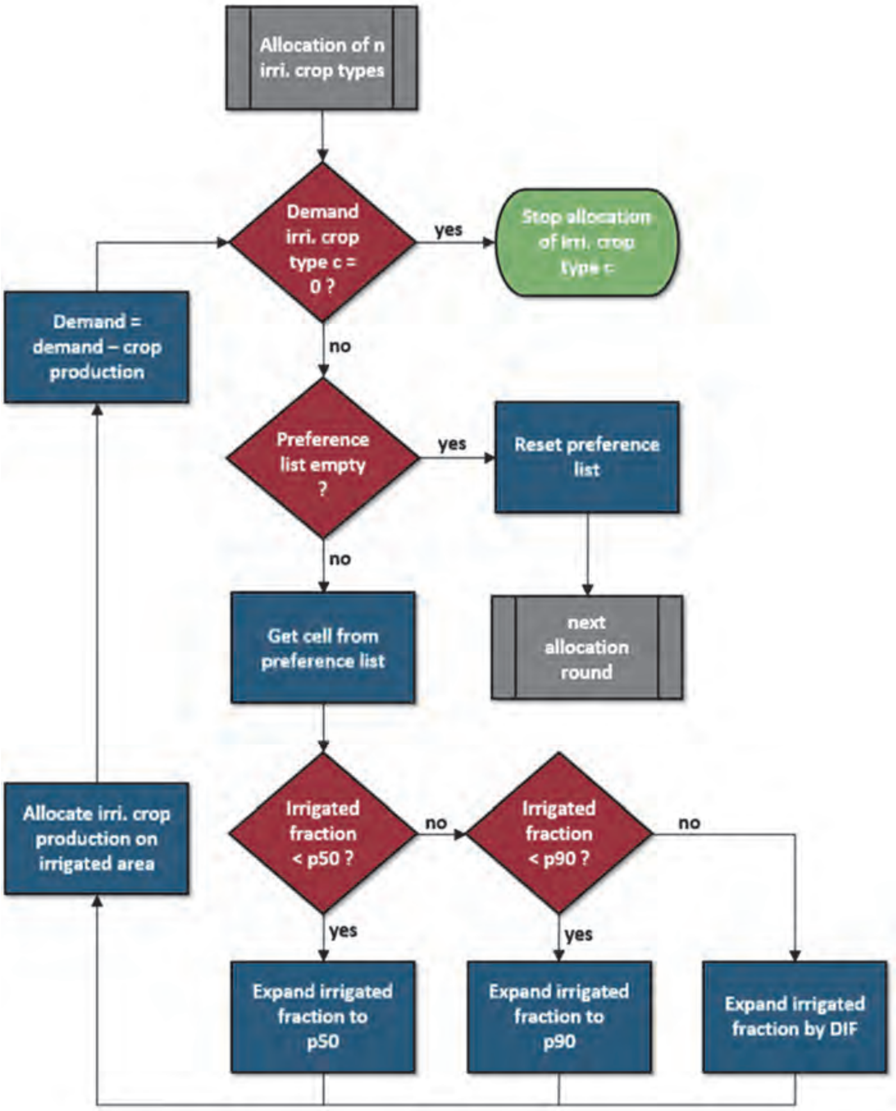

Figure B 1: Flowchart for allocating irrigated crop production to new irrigated areas (first round of algorithm). p50 = 50th percentile (median), p90 = 90th percentile, DIF = demand increase factor.

Table B 1: Input data used in this report for simulations with LandSHIFT

Spatial level	Model variable	Purpose	Comment	Source
Country	Crop production, area harvested	Baseline definition	FAOSTAT data downloaded in 01/2021 from http://www.fao.org/faostat/en/#data/QC	FAO (2021)
	physical area, crop production rainfed/irrigated	Baseline definition	Results from the SPAM model for 2010 on 5 arc minute resolution aggregated on country-level to split crop production from FAOSTAT into irrigated and rainfed parts and to convert harvested into physical area	IFPRI (2019)
	change in crop yield	Scenario simulation	Assumptions from two different model runs of the REMIND-MAgPIE modeling framework; trends applied on the potential crop yields on grid cell level	Bauer et al. (2017)
	change in crop production	Scenario simulation	Assumptions from two different model runs of the REMIND-MAgPIE modeling framework, trends applied on production volumes on country level	Bauer et al. (2017)
	Population change	Scenario Simulation	Assumptions (total number, urban and rural share) taken from country-level SSP database for SSP2; applied on population on country level	KC & Lutz (2017), Rihahi et al. (2017)
Grid, 30 arc minutes	Potential Crop yields rainfed & irrigated	Biomass productivity	Potential crop yields were calculated by LPJmL for current climate conditions, defined by the reference period 1971-2000. For this purpose, data was taken from the "CRU TS 2.1" gridded dataset for monthly precipitation, air temperature, cloud cover, and frequency of wet days.	Bondeau et al. (2007) Mitchell & Jones (2005)
Grid, 5 arc minutes	Land use/land cover type	Baseline definition	Remote sensing product on land cover from ESA Climate Change Initiative (CCI).	ESA (2019)
	Fraction of irrigated area	Baseline definition	Current fraction of irrigated area per grid cell was taken from Digital Global Map of Irrigation Areas	Siebert et al. (2013)
	Population density	Baseline definition	Population density for each cell was derived from HYDE https://themasites.pbl.nl/tridion/en/themasites/hyde/download/index-2.html	Klein-Goldewijk (2005)
	Terrain slope	Preference ranking	Grid level information on terrain slope is based upon data from the agro-ecological zones project.	IIASA & FAO (2000)
	River network density	Preference ranking	River network density was calculated as line density of streams per cell based on "A Simple Global River Bankfull Width and Depth Database" http://gaia.geosci.unc.edu/rivers/	Andreadis et al. (2013)

	Road infra-structure	Preference ranking	Information on road infrastructure was obtained from the gRoads Dataset v1.	CIESIN & ITOS (2013)
	Nature Conser-vation areas	Preference ranking	The location of nature conservation areas was de-rived from the world database on protected areas.	UNEP-WCMC & IUCN (2013)
Irrigation units	River (sub) ba-sins	Irrigation reference space	(sub) river basins that are not larger than 20,000 km² form the general irrigation response unit, pro-vided by the global water Model WaterGAP3	Brauman et al. (2016)
	GAEZ	Irrigation reference space	18 Global Agro Ecological Zones (GAEZ), repre-sent natural growing conditions, used to form larger irrigation units in case that river (sub) basins do not fulfil minimum requirements, https://www.gtap.agecon.purdue.edu/re-sources/res_display.asp?RecordID=3184	Ramankutty et al. (2007)

Table B 2: Factors for preference ranking for irrigated crop types with LandSHIFT

	Factor	**Correlation**	**Co-domain**	**Irrigation specific**
Suitability	Terrain slope	negative	0 to 1	no
	Potential irrigated crop yield	positive	0 to 1	no
	Neighborhood to cropland cells	positive	0 to 1	no
	Population density	positive	0 to 1	no
	Road infrastructure	positive	0 to 1	no
	River network density	positive	0 to 1	yes
Constraints	Nature conservation area		boolean	no
	Minimum yield gain		boolean	yes
	Minimum irrigated yield		boolean	yes

Table B 3: Mapping crop classes of LandSHIFT and REMIND-MAgPIE

LandSHIFT crop classes	REMIND-MAgPIE crop classes
temperate cereals	tece
tropical cereals	trce
maize	maize
annual oil crops	groudnut, sunflower, rapeseed, oilpalm
pulses	puls_pro
rice	rice_pro
temperate roots and tubers	potato, sugar_beet
cotton	cotton_pro
soybeans	soybean
sugar cane	sugr_cane
fodder	foddr
other crops	others, cassava_sp

Table B 4: Production trends (factors) of irrigated crop classes for scenario SSP2_26

		2015	2020	2025	2030	2035	2040
AFR	temperate cereals	1.00	1.07	0.78	0.83	0.90	1.55
	tropical cereals	1.00	1.00	1.08	0.96	1.71	1.83
	maize	1.00	1.09	2.61	12.89	37.00	39.34
	annual oil crops	1.00	1.09	1.17	1.26	1.36	1.45
	pulses	1.00	4.29	5.22	5.47	8.54	8.25
	rice	1.00	1.35	2.08	2.86	2.06	2.19
	temperate roots & tubers	1.00	1.11	1.22	1.33	1.44	1.54
	cotton	1.00	1.11	2.99	1.75	3.46	3.21
	soybeans	1.00	1.00	1.00	1.00	1.00	1.00
	sugarcane	1.00	1.16	1.24	2.80	2.49	2.65
	other crops	1.00	1.00	1.38	5.82	9.67	10.27
CPA	temperate cereals	1.00	2.49	4.30	4.91	5.09	5.23
	tropical cereals	1.00	1.36	1.43	1.48	1.53	1.58
	maize	1.00	0.32	0.47	0.29	2.83	2.89
	annual oil crops	1.00	1.00	1.00	1.00	1.00	1.00
	pulses	1.00	1.00	1.00	1.00	1.00	1.00
	rice	1.00	1.22	2.68	2.78	2.66	2.73
	temperate roots & tubers	1.00	1.05	1.02	1.03	1.01	0.97
	cotton	1.00	1.00	1.00	1.00	1.00	1.00
	soybeans	1.00	1.26	1.54	1.60	1.86	2.00
	sugarcane	1.00	1.00	1.00	1.00	1.00	1.00
	other crops	1.00	1.00	1.00	1.00	1.00	1.00
EUR	temperate cereals	1.00	0.94	1.01	1.08	1.16	1.48
	tropical cereals	1.00	1.00	1.00	1.00	1.00	1.00
	maize	1.00	1.04	1.00	0.95	0.90	0.85
	annual oil crops	1.00	1.01	1.01	1.02	1.02	1.02
	pulses	1.00	1.00	1.00	1.00	1.00	1.00
	rice	1.00	1.00	1.00	1.00	1.00	0.99
	temperate roots & tubers	1.00	1.05	1.05	1.05	1.05	1.04
	cotton	1.00	1.00	1.00	0.99	0.98	0.97
	soybeans	1.00	1.00	1.00	1.00	1.00	1.00
	sugarcane						
	other crops	1.00	1.00	1.00	1.01	1.01	1.02
FSU	temperate cereals	1.00	1.08	1.14	1.22	1.26	1.27
	tropical cereals						
	maize	1.00	1.05	1.30	1.89	2.31	2.39
	annual oil crops	1.00	1.04	1.07	1.11	2.95	4.92
	pulses	1.00	1.00	1.00	1.00	1.00	1.00
	rice	1.00	1.06	0.98	0.40	0.07	0.07
	temperate roots & tubers	1.00	0.87	0.90	0.75	0.72	0.52
	cotton	1.00	1.01	1.00	1.01	1.00	0.99
	soybeans	1.00	1.00	1.00	2.83	9.33	18.00
	sugarcane						
	other crops	1.00	1.13	1.21	1.27	0.64	0.66
LAM	temperate cereals	1.00	1.02	1.07	1.10	1.11	1.11
	tropical cereals	1.00	1.06	55.59	57.26	57.74	57.74
	maize	1.00	2.48	2.96	1.98	2.37	2.94
	annual oil crops	1.00	1.00	1.00	1.00	1.00	1.00
	pulses	1.00	1.00	1.00	1.00	1.00	1.00
	rice	1.00	4.11	4.30	5.75	5.80	2.63
	temperate roots & tubers	1.00	1.03	1.05	1.06	1.06	1.07
	cotton	1.00	1.00	1.00	1.00	1.00	1.00
	soybeans	1.00	1.06	1.12	3.62	2.70	2.37
	sugarcane	1.00	1.32	1.59	1.61	1.62	1.62
	other crops	1.00	1.70	2.00	1.46	2.42	2.08

Table B 5: Production trends (factors) of irrigated crop classes for scenario SSP2_45

		2015	2020	2025	2030	2035	2040
AFR	temperate cereals	1.00	1.07	0.78	0.85	0.93	0.49
	tropical cereals	1.00	1.00	1.08	0.94	1.33	1.75
	maize	1.00	1.09	4.41	16.07	38.03	41.66
	annual oil crops	1.00	1.09	1.18	1.28	1.40	1.51
	pulses	1.00	4.29	5.30	5.71	7.79	10.12
	rice	1.00	1.35	1.40	3.02	3.11	2.29
	temperate roots and tubers	1.00	1.11	1.22	1.33	1.44	1.54
	cotton	1.00	1.11	3.01	3.27	1.95	1.51
	soybeans	1.00	1.00	1.00	1.00	1.00	1.00
	sugarcane	1.00	1.16	1.25	3.31	2.56	2.77
	other crops	1.00	1.00	1.82	7.26	10.05	10.89
CPA	temperate cereals	1.00	2.49	4.30	3.60	5.01	3.31
	tropical cereals	1.00	1.36	1.43	1.48	1.51	1.53
	maize	1.00	0.32	0.46	1.74	0.30	1.14
	annual oil crops	1.00	1.00	1.00	1.00	1.00	1.00
	pulses	1.00	1.00	1.00	1.00	1.00	1.00
	rice	1.00	1.22	2.68	2.77	2.83	2.87
	temperate roots and tubers	1.00	1.05	1.01	1.04	1.01	0.97
	cotton	1.00	1.00	1.00	1.00	1.00	1.00
	soybeans	1.00	1.26	1.51	1.56	1.59	1.61
	sugarcane	1.00	1.00	1.00	1.00	1.00	1.00
	other crops	1.00	1.00	1.00	1.00	1.00	1.00
EUR	temperate cereals	1.00	0.94	1.01	1.08	1.16	1.16
	tropical cereals	1.00	1.00	1.00	1.00	1.00	1.00
	maize	1.00	1.04	1.00	0.95	0.90	0.90
	annual oil crops	1.00	1.01	1.01	1.02	1.02	1.02
	pulses	1.00	1.00	1.00	1.00	1.00	1.00
	rice	1.00	1.00	1.00	1.00	1.00	0.99
	temperate roots and tubers	1.00	1.05	1.05	1.05	1.15	1.36
	cotton	1.00	1.00	1.00	0.99	0.98	0.97
	soybeans	1.00	1.00	1.00	1.00	1.00	1.00
	sugarcane						
	other crops	1.00	1.00	1.00	1.01	1.01	1.02
FSU	temperate cereals	1.00	1.08	1.14	1.16	1.24	1.21
	tropical cereals						
	maize	1.00	1.05	1.09	1.85	1.91	1.93
	annual oil crops	1.00	1.04	1.07	1.10	0.14	2.17
	pulses	1.00	1.00	1.00	1.00	1.00	1.00
	rice	1.00	1.06	1.09	1.13	0.45	0.40
	temperate roots and tubers	1.00	0.87	0.91	0.76	0.66	0.70
	cotton	1.00	1.01	1.01	1.00	0.99	0.97
	soybeans	1.00	1.00	1.00	1.83	8.33	9.33
	sugarcane						
	other crops	1.00	1.13	1.20	1.24	1.27	1.20
LAM	temperate cereals	1.00	1.02	1.07	1.11	1.13	1.13
	tropical cereals	1.00	1.06	55.58	57.73	59.16	59.98
	maize	1.00	2.48	2.97	2.11	2.16	2.68
	annual oil crops	1.00	1.00	1.00	1.00	1.00	1.00
	pulses	1.00	1.00	1.00	1.00	1.00	1.00
	rice	1.00	4.11	4.31	4.47	4.70	4.90
	temperate roots and tubers	1.00	1.03	1.05	1.06	1.06	1.07
	cotton	1.00	1.00	1.00	1.00	1.00	1.00
	soybeans	1.00	1.06	1.12	3.26	3.62	4.00
	sugarcane	1.00	1.32	1.59	1.62	1.66	1.69
	other crops	1.00	1.70	2.00	1.89	1.65	1.21

Table B 6: Yield trends (factors) of irrigated crop classes for scenario SSP2_26

		2015	2020	2025	2030	2035	2040
AFR	temperate cereals	1.00	1.09	1.18	1.26	1.36	1.45
	tropical cereals	1.00	1.14	1.23	1.25	1.31	1.40
	maize	1.00	1.09	1.32	1.03	1.00	1.06
	rice	1.00	1.04	1.16	1.24	1.58	1.68
	pulses	1.00	1.39	1.46	1.56	1.63	1.74
	soybeans	1.00	1.00	1.00	1.00	1.00	1.00
	cotton	1.00	1.10	1.49	1.47	1.73	1.74
	sugarcane	1.00	1.13	1.21	1.12	1.55	1.65
	annual oil crops	1.00	1.09	1.17	1.26	1.36	1.45
	temperate roots and tubers	1.00	1.09	1.16	1.24	1.41	1.50
	other crops	1.00	1.07	1.55	1.57	1.59	1.69
CPA	temperate cereals	1.00	1.06	1.11	1.15	1.19	1.22
	tropical cereals	1.00	1.06	1.12	1.16	1.20	1.23
	maize	1.00	1.02	1.10	1.09	1.27	1.30
	rice	1.00	1.04	1.00	1.04	1.08	1.11
	pulses	1.00	1.00	1.00	1.00	1.00	1.00
	soybeans	1.00	1.03	1.11	1.15	1.20	1.23
	cotton	1.00	1.00	1.00	1.00	1.00	1.00
	sugarcane	1.00	1.00	1.00	1.00	1.00	1.00
	annual oil crops	1.00	1.00	1.00	1.00	1.00	1.00
	temperate roots and tubers	1.00	1.14	1.22	1.27	1.29	1.31
	other crops	1.00	1.00	1.00	1.00	1.00	1.00
EUR	temperate cereals	1.00	0.99	1.00	1.01	1.02	1.03
	tropical cereals	1.00	1.00	1.00	1.00	1.00	1.00
	maize	1.00	1.00	1.00	1.00	1.00	0.97
	rice	1.00	1.00	1.00	1.00	1.00	1.00
	pulses	1.00	1.00	1.00	1.00	1.00	1.00
	soybeans	1.00	1.00	1.00	1.00	1.00	1.00
	cotton	1.00	1.00	1.00	1.00	1.00	1.00
	sugarcane	1.00	1.00	1.00	1.00	1.00	1.00
	annual oil crops	1.00	1.00	1.00	1.00	1.00	1.00
	temperate roots and tubers	1.00	1.00	1.00	1.00	1.00	1.00
	other crops	1.00	1.00	1.00	1.00	1.00	1.00
FSU	temperate cereals	1.00	1.02	1.05	1.03	0.97	1.00
	tropical cereals						
	maize	1.00	1.05	1.11	1.15	1.22	1.26
	rice	1.00	1.04	1.17	1.21	1.28	1.33
	pulses	1.00	1.00	1.00	1.00	1.00	1.00
	soybeans	1.00	1.05	1.09	1.50	1.94	2.12
	cotton	1.00	1.05	1.12	1.32	1.37	1.46
	sugarcane						
	annual oil crops	1.00	1.04	1.08	1.12	1.02	1.51
	temperate roots and tubers	1.00	1.04	1.09	1.19	1.43	1.58
	other crops	1.00	1.08	1.13	1.16	1.83	1.90
LAM	temperate cereals	1.00	1.09	1.14	1.18	1.19	1.19
	tropical cereals	1.00	1.06	1.08	1.11	1.12	1.12
	maize	1.00	1.35	1.89	1.67	1.73	1.79
	rice	1.00	1.05	1.10	1.26	1.27	1.45
	pulses	1.00	1.00	1.00	1.00	1.00	1.00
	soybeans	1.00	1.06	1.12	1.28	1.24	1.25
	cotton	1.00	1.00	1.00	1.00	1.00	1.00
	sugarcane	1.00	1.06	1.12	1.16	1.17	1.17
	annual oil crops	1.00	1.00	1.00	1.00	1.00	1.00
	temperate roots and tubers	1.00	1.07	1.12	1.15	1.16	1.16
	other crops	1.00	0.73	0.72	0.91	0.71	0.69

Table B 7: Yield trends (factors) of irrigated crop classes for scenario SSP2_45

		2015	2020	2025	2030	2035	2040
AFR	temperate cereals	1.00	1.09	1.19	1.29	1.40	1.53
	tropical cereals	1.00	1.14	1.24	1.34	1.39	1.51
	maize	1.00	1.09	1.39	1.02	1.02	1.09
	rice	1.00	1.04	1.10	1.25	1.52	1.76
	pulses	1.00	1.39	1.47	1.59	1.78	1.80
	soybeans	1.00	1.00	1.00	1.00	1.00	1.00
	cotton	1.00	1.10	1.50	1.63	1.64	1.51
	sugarcane	1.00	1.13	1.22	1.11	1.59	1.72
	annual oil crops	1.00	1.09	1.18	1.28	1.40	1.51
	temperate roots and tubers	1.00	1.09	1.17	1.27	1.46	1.58
	other crops	1.00	1.07	1.73	1.59	1.64	1.77
CPA	temperate cereals	1.00	1.06	1.11	1.14	1.17	1.19
	tropical cereals	1.00	1.06	1.12	1.16	1.18	1.20
	maize	1.00	1.02	1.10	1.20	1.10	1.21
	rice	1.00	1.04	1.00	1.04	1.06	1.08
	pulses	1.00	1.00	1.00	1.00	1.00	1.00
	soybeans	1.00	1.03	1.11	1.15	1.17	1.19
	cotton	1.00	1.00	1.00	1.00	1.00	1.00
	sugarcane	1.00	1.00	1.00	1.00	1.00	1.00
	annual oil crops	1.00	1.00	1.00	1.00	1.00	1.00
	temperate roots and tubers	1.00	1.14	1.22	1.26	1.29	1.31
	other crops	1.00	1.00	1.00	1.00	1.00	1.00
EUR	temperate cereals	1.00	0.99	1.00	1.01	1.02	1.02
	tropical cereals	1.00	1.00	1.00	1.00	1.00	1.00
	maize	1.00	1.00	1.00	1.00	1.00	1.00
	rice	1.00	1.00	1.00	1.00	1.00	1.00
	pulses	1.00	1.00	1.00	1.00	1.00	1.00
	soybeans	1.00	1.00	1.00	1.00	1.00	1.00
	cotton	1.00	1.00	1.00	1.00	1.00	1.00
	sugarcane	1.00	1.00	1.00	1.00	1.00	1.00
	annual oil crops	1.00	1.00	1.00	1.00	1.00	1.00
	temperate roots and tubers	1.00	1.00	1.00	1.00	0.92	0.82
	other crops	1.00	1.00	1.00	1.00	1.00	1.00
FSU	temperate cereals	1.00	1.02	1.04	1.13	1.05	1.03
	tropical cereals						
	maize	1.00	1.05	1.09	1.13	1.16	1.17
	rice	1.00	1.04	1.08	1.12	1.22	1.23
	pulses	1.00	1.00	1.00	1.00	1.00	1.00
	soybeans	1.00	1.05	1.09	1.35	1.79	1.92
	cotton	1.00	1.05	1.11	1.27	1.34	1.36
	sugarcane	1.00	1.00	1.00	1.00	1.00	1.00
	annual oil crops	1.00	1.04	1.08	1.11	0.69	0.97
	temperate roots and tubers	1.00	1.04	1.09	1.16	1.30	1.52
	other crops	1.00	1.08	1.10	1.17	1.19	1.24
LAM	temperate cereals	1.00	1.09	1.14	1.19	1.23	1.25
	tropical cereals	1.00	1.06	1.08	1.12	1.15	1.16
	maize	1.00	1.35	1.89	1.67	1.71	1.80
	rice	1.00	1.05	1.10	1.15	1.17	1.18
	pulses	1.00	1.00	1.00	1.00	1.00	1.00
	soybeans	1.00	1.06	1.12	1.28	1.33	1.36
	cotton	1.00	1.00	1.00	1.00	1.00	1.00
	sugarcane	1.00	1.06	1.12	1.17	1.20	1.22
	annual oil crops	1.00	1.00	1.00	1.00	1.00	1.00
	temperate roots and tubers	1.00	1.07	1.12	1.16	1.19	1.20
	other crops	1.00	0.73	0.73	0.79	0.89	1.20

References Annex B

Andreadis, K. M., Schumann, G. J.-P., & Pavelsky, T. (2013). A simple global river bankfull width and depth database. *Water Resources Research*, *49*(10), 7164–7168. https://doi.org/10.1002/wrcr.20440

Bauer, N., Calvin, K., Emmerling, J., Fricko, O., Fujimori, S., Hilaire, J., Eom, J., Krey, V., Kriegler, E., Mouratiadou, I., Sytze de Boer, H., van den Berg, M., Carrara, S., Daioglou, V., Drouet, L., Edmonds, J. E., Gernaat, D., Havlik, P., Johnson, N., . . . van Vuuren, D. P. (2017). *Shared Socio-Economic Pathways of the Energy Sector – Quantifying the Narratives* (Vol. 42). https://doi.org/10.1016/j.gloenvcha.2016.07.006

Bondeau, A., Smith, P. C., Zaehle, S., Schapoff, S., Lucht, W., Cramer, W., Gerten, D., Lotze-Campen, H., Müller, C., Reichstein, M., & Smith, B. (2007). Modelling the role of agriculture for the 20th century global terrestrial carbon balance. *Global Change Biology*, *13*(3), 679–706. https://doi.org/10.1111/j.1365-2486.2006.01305.x

Brauman, K. A., Richter, B. D., Postel, S., Malsy, M., & Flörke, M. (2016). Water depletion: An improved metric for incorporating seasonal and dry-year water scarcity into water risk assessments. *Elementa: Science of the Anthropocene*, *4*, 83. https://doi.org/10.12952/journal.elementa.000083

CIESIN (Center For International Earth Science Information Network); ITOS (Information Technology Outreach Services) (2013): Global Roads Open Access Data Set, Version 1 (gROADSv1). DOI: 10.7927/H4VD6WCT

Eisner, S. (2016). *Comprehensive evaluation of the WaterGAP3 model across climatic, physiographic, and anthropogenic gradients*. Ph.D. thesis. University of Kassel.

ESA Climate Change Initiative. (2017). *Land Cover led by UCLouvain (2017).* http://maps.elie.ucl.ac.be/CCI/viewer/download.php

Food and Agriculture Organization of the United Nations. (2021). *FAOSTAT: database*. http://www.fao.org/faostat/en/#data/QC

International Food Policy Research Institute. (2019). *Global Spatially-Disaggregated Crop Production Statistics Data for 2010 Version 2.0.* Harvard Dataverse, V4.

IIASA (International Institute for Applied Systems Analysis); FAO (Food and Agriculture Organization of the United Nations) (2000). *Global Agroecological Zones*. Plate 9-Median of Terrain Slopes. Global Agro-Ecological Zones CD-ROM

KC, S., & Lutz, W. (2017). The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. *Global Environmental Change*, *42*, 181–192. https://doi.org/10.1016/j.gloenvcha.2014.06.004

Klein-Goldewijk, K. (2005). Three centuries of global population growth: A spatial referenced population (density) database for 1700-2000. *Population and Environment, 26*(4), pp. 343-367, doi: http://dx.doi.org/10.1007/s11111-005-3346-7

Mitchell, T.D.,and Jones, P.D. (2005). An improved method of constructing a database of monthly climate observations and associated high-resolution grids. *International Journal of Climatology, 5*, 693-712. Doi: 10.1002/joc.1181

Ramankutty, N., Hertel, T., Lee, H.-L., & Rose, S. K. (2007). Global agricultural land-use data for integrated assessment modeling. In M. E. Schlesinger, H. S. Kheshgi, J. Smith, F. C. de La Chesnaye, J. M. Reilly, T. Wilson, & C. Kolstad (Eds.), *Human-Induced Climate Change* (pp. 252–265). Cambridge University Press. https://doi.org/10.1017/CBO9780511619472.025

Schaldach, R., Alcamo, J., Koch, J., Kölking, C., Lapola, D. M., Schüngel, J., & Priess, J. A. (2011). An integrated approach to modelling land-use change on continental and global scales. *Environmental Modelling & Software*, *26*(8), 1041–1051.

Schüngel, J., Stuch, B., Fohry, C., & Schaldach, R. (2021). Impacts of land cover initialization on globa land use simulations. *Environmental Modelling & Software*, submitted.

Siebert, S., Henrich, V., Frenken, K., & Burke, J. (2013). *Update of the Digital Global Map of Irrigation Areas to Version 5*. Rheinische Friedrich-Wilhelms-Universität, Bonn, Germany and FAO - Food and Agriculture Organization of the United Nations, Rome, Italy.

UNEP-WCMC (United Nations Environment Programme World Conservation Monitoring Centre); IUCN (International Union for Conservation of Nature and Natural Resources) (2013): Protected planet. The World Database on Protected Areas (WDPA). Camebridge, www.protectedplanet.net

Bisher erschienene Hefte der Schriftenreihe HYDROLOGIE / WASSERWIRTSCHAFT

Heft	Jahr	Autor und Titel
1	1983	**Klatt, Peter** Vorhersage von Hochwasser aus radargemessenem und prognostiziertem Niederschlag
2	1983	**Scheider, Klaus** Modell zur gleichzeitigen Erzeugung von Tagesabflussdaten an mehreren Stellen eines Einzugsgebietes
3	1984	**Strübing, Gert** Satellitendaten als Basis der Bestimmung von monatlichen Abflüssen für wasserwirtschaftliche Planungen
4	1985	**Harboe, Ricardo** Optimaler Betrieb wasserwirtschaftlicher Verbundsysteme mit Speichern und anderen Anlagen
5	1986	**Tegtmeier, Ulrike** Wasserwirtschaftliche Projektbewertung – Methoden und Anwendungsbeispiele
6	1987	**Richter, Karl Gerd** Vergleichende hydrologische Untersuchungen des Hochwasserablaufes in Testeinzugsgebieten mit unterschiedlicher Bebauungsdichte
7	1989	**Salas, Edgar** Anwendung der Bayesschen Theorie auf wasserwirtschaftliche Planungen mit hydrologischen Datenreihen
8	1990	**Vogt, Roland** Stauraumverlandung – Naturmessung und Computersimulation
9	1992	**Tiedt, Michael** Freizeitnutzung als Komponente der Wasserwirtschaftlichen Projektbewertung
10	1993	**Gyau-Boakye, Philip** Filling Gaps in Hydrological Runoff Data Series in West-Africa Ergänzung lückenhafter Abflussreihen in West-Afrika
11	1993	**Schumann, Andreas H.** Der Einfluss von Veränderungen der Umweltbedingungen und sozio-ökonomischer Faktoren auf Hydrologie und Wasserwirtschaft
12	1993	**Fett, Werner** Die Nutzung räumlich hoch aufgelöster Gebietsinformationen für die Simulation von Hochwasserganglinien in humiden Mittelgebirgslandschaften

Heft	Jahr	Autor und Titel
13	1994	**Papadakis, Ioannis** Berechnung historischer Abflüsse mit Hilfe multispektraler und multitemporaler digitaler Satellitenbilder
14	1995	**Schultz, G.A. (Hrsg.)** Verfügbarkeit von Wasser Beiträge zur 8. wissenschaftlichen Tagung des DVWK vom 22.-23.03.1995 an der Ruhr-Universität Bochum
15	1996	**Su, Zhongbo** Remote Sensing Applied to Hydrology: The Sauer River Basin Study Fernerkundung angewandt in der Hydrologie: Die Sauer-Einzugsgebiets-Studie
16	1997	**Wolbring, Frank** Wissensbasierte Methoden für den Betrieb von Talsperren
17	1998	**Hornbogen, Martin** Die Planung von Wasserversorgungssystemen auf der Basis des Nachhaltigkeitsprinzips
18	2002	**Schumann, Andreas H. (Hrsg.)** Proceedings Workshop HydroGIS NRW 2002 23.05.2002 Ruhr-Universität Bochum
19	2003	**Quirmbach, Markus** Nutzung von Wetterradardaten für Niederschlags- und Abflussvorhersagen in urbanen Einzugsgebieten
20	2006	**Brass, Carsten** Betriebsoptimierung von Talsperrensystemen mittels Stochastisch Dynamischer Programmierung (SDP) unter Berücksichtigung veränderlicher Ziele und Randbedingungen
21	2006	**Dietrich, Jörg** Entwicklung einer Methodik zur systemanalytischen Unterstützung adaptierbarer Entscheidungsprozesse bei der integrierten Flussgebietsbewirtschaftung
22	2006	**Gattke, Christian** Modellvergleiche zur Untersuchung struktureller Unsicherheiten – Anwendung objektorientierter Methoden in der hydrologischen Modellierung
23	2009	**Schumann, Andreas H. (Hrsg.)** Verbundvorhaben Entwicklung integrativer Lösungen für das operationelle Hochwassermanagement am Beispiel der Mulde – Abschlussbericht

Heft	Jahr	Autor und Titel
24	2009	**Schumann, Andreas H. (Hrsg.)** Integrative Nutzung des technischen Hochwasserrückhalts in Poldern und Talsperren am Beispiel des Flussgebiets der Unstrut
25	2009	**Klein, Bastian** Ermittlung von Ganglinien für die risikoorientierte Hochwasserbemessung von Talsperren
26	2010	**Wisser, Dominik** Modeling of Irrigation and Reservoirs in Regional and global Water Cycles
27	2013	**Nijssen, David** Improving spatiality in decision making for river basin management
28	2015	**Schulte, Markus** Anwendung von Copula-Modellen in der Hochwasserstatistik zur Planung technischer Rückhaltemaßnahmen
29	2016	**Tyralla, Christoph** Identifikation und Reduktion struktureller Unsicherheiten in hydrologischen Modellen
30	2019	**Oppel, Henning** Entwicklung eines selbstkalibrierenden Niederschlags-Abfluss Modells auf Basis der geomorphologischen Einheitsganglinie und Methoden des Machine Learning
31	2019	**Mewes, Benjamin** Application of Machine Learning enhanced Agent-based Techniques in Hydrology and Water Resource Management
32	2021	**Flörke, Martina; Onigkeit, Janina; Oppel, Henning (Eds.)** Water Resources as Important Factor in the Energy Transition at Local and Global Scale. Final Report of the joint project WANDEL

Lehrstuhl für Ingenieurhydrologie und Wasserwirtschaft
Ruhr-Universität Bochum, 2021

Universitätsstraße 150, 44801 Bochum
Tel. +49 (0)234 32 - 24693, Fax. - 14153

ISSN 0949-5975