Pieces to the Puzzle of the Water-Energy-Food Nexus:

Considerations of Managed Aquifer Recharge, Conceptual Analyses, and Computations of Interlinkages

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To all grandparents who devote time to their grandchildren, allowing parents to build careers and contribute to a future worth inheriting.

Für alle Großeltern, die ihren Enkeln Zeit widmen, um den Eltern zu ermöglichen, sich beruflich zu entfalten und zu einer enkeltauglichen Zukunft beizutragen.

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List of Abbreviations

AEZ	Agricultural Ecosystem Zoning
AGU	American Geophysical Union
ALF	Analytical Livelihoods Framework
APA	American Psychological Association
CCS	Carbon Capture and Storage
CGIAR	Consultative Group on International Agricultural Research
CH	Switzerland
CLEWS	Climate change Land-use Energy Water Strategies
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalent
CSP	Concentrated Solar Power
CSRD	Corporate Sustainability Reporting Directive
DAFNE	Decision-Analytic Framework to explore the Water-Energy-Food Nexus
DE	Germany
DEM	Digital Elevation Model
ENTSO-E	European Network of Transmission System Operators for Electricity
ES	Spain
ESG	Environmental, Social, and Governance.
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FEW	Food-Energy-Water
FR	France
GIS	Geographic Information System
IAD	Institutional Analysis and Development
IAH	International Association of Hydrogeologists
IEA	International Energy Agency
IGRAC	International Groundwater Resources Assessment Centre
IIASA	International Institute for Applied Systems Analysis
INOWAS	Innovative Groundwater Solutions
INRM	Integrated Natural Resources Management
IRENA	International Renewable Energy Agency
ISWM	Integrated Solid Waste Management

IT	Italy
IWRM	Integrated Water Resources Management
JHU	Johns Hopkins University
KfW	German Development Bank (Kreditanstalt für Wiederaufbau)
LDM	Lockdown Measures
LEAP	Long-range Energy Alternatives Planning System
MAG	Ministry of Agriculture and Livestock of Costa Rica (Ministerio de Agricultura y Ganaderia of Costa Rica)
MAR	Managed Aquifer Recharge
MCDA	Multi-Criteria Decision Analysis
MuSIASEM	Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism
NAAS	Networks of Adjacent Action Situations
OECD	Organisation for Economic Co-operation and Development
OnSSET	Open Source Spatial Electrification Tool
PCM	Precautionary Measures
SDG	Sustainable Development Goals
TU	Technical University
UNDESA	United Nations Department of Economic and Social Affairs
UNECE	United Nations Economic Commission for Europe
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNU-FLORES	United Nations University Institute for Integrated Management of Material Fluxes and of Resources
WEAP	Water Evaluation And Planning system
WEF	Water-Energy-Food
WEFE	Water-Energy-Food-Ecosystems
WEF-PIK	Water-Energy-Food Nexus considering Policies, Institutions and Knowledge
WLC	Weighted Linear Combination
WSW	Water-Soil-Waste

Abstract

Rising demands for water, energy and food, in combination with population growth and climate change, threaten human well-being and intensify overuse of natural resources. The Water-Energy-Food Nexus (WEF-Nexus) has emerged as an integrated approach to increase efficiency across these sectors, reduce said overuse and support sustainable development.

While many studies and projects have been carried out considering the nexus between water, food and energy, a scholarly debate is still ongoing on what the WEF-Nexus exactly is. This dissertation aims to contribute to this debate through theoretical and practical research.

The dissertation first considers Managed Aquifer Recharge (MAR) in Costa Rica. A multi-criteria decision analysis using a Geographic Information System (GIS) shows that more than 30% of the country is highly or very highly suitable for using the MAR-type spreading method. MAR can be a promising and versatile water management technology to restore groundwater levels, to use aquifers as water buffers between supply and demand periods, improve water quality as well as provide additional benefits. By discussing the applicability of MAR in the Lake Arenal and Paacume project – both facing major challenges at the interface of water, energy and food – the need for a WEF-Nexus approach is shown.

To understand what constitutes the WEF-Nexus, the dissertation offers conceptual analyses based on a systematic literature review of 73 conceptual articles on the WEF-Nexus from the past two decades. The analyses show that the WEF-Nexus is building on preexisting integrated approaches, yet with the goal of shifting from integration within sectors to cross-sector integration and improving policy coherence. While the results confirm that there is no widely agreed upon definition of the WEF-Nexus, the dissertation presents an overview of 32 different Nexus Frameworks, roughly a dozen main features of the WEF-Nexus and up to 21 different aspects that may be integrated within the WEF-Nexus. Examples of features are interdisciplinarity, transdisciplinarity or enabling the participation and inclusion of stakeholders. Emerging features of the WEF-Nexus include the development of WEF-Nexus indicators, the incorporation of the political and social dimension, and a focus on innovation.

To apply the WEF-Nexus, a detailed understanding of the many individual biophysical interlinkages between the domains of water, food and energy is required. One such detailed analysis is provided in the dissertation through computations of water-electricity interlinkages at the sub-annual scale in the highly dynamic period of the

COVID-19 pandemic. During the lockdown measures in Europe, the water footprint of thermal electricity generation was reduced by 21% compared to the same time of previous years. This is due to three factors: a medium-term shift in the electricity mix in the years before the pandemic towards less water-intensive electricity generation, and — during the lockdowns — a short-term shift to less water-intensive generation and a reduction in overall electricity generation. The results further show the changes in virtual water trade among five European countries and how imports and exports shifted.

Based on the methodology of this analysis, data availability was assessed to outline a tool to monitor Europe’s water footprint and virtual water trade in near real time. Such a tool could be used in a WEF-Nexus Framework to increase awareness about water use in electricity generation, incentivize private actors to decrease their water footprint and create incentives in the electricity market to reduce water intensity in electricity generation e.g., through pricing mechanisms.

Through these results, the dissertation advances the WEF-Nexus conceptually and practically so that it can better tackle challenges at the interface of water, energy, and food, thereby supporting sustainable development in Costa Rica, Europe, and beyond.

Zusammenfassung

Steigende Bedarfe an Wasser, Energie und Nahrungsmitteln in Verbindung mit Bevölkerungswachstum und Klimawandel bedrohen das menschliche Wohlergehen und intensivieren die Überbeanspruchung natürlicher Ressourcen. Der Wasser-Energie-Nahrungsmittel Nexus (WEF-Nexus) hat sich als integrierter Ansatz herauskristallisiert, um zur Effizienzsteigerungen in diesen Sektoren, zur Verringerung der Ressourcenbelastung und zur Unterstützung einer nachhaltigen Entwicklung beizutragen.

Obgleich viele Studien und Projekte an den Schnittstellen von Wasser, Energie und Nahrungsmitteln durchgeführt wurden, besteht weiterhin ein wissenschaftlicher Diskurs darüber, was den WEF-Nexus genau ausmacht. Diese Dissertation soll durch theoretische und angewandte Untersuchungen einen Beitrag zu dieser Debatte leisten.

Die Dissertation befasst sich zunächst mit der kontrollierten Grundwasseranreicherung (Managed Aquifer Recharge, MAR) in Costa Rica. Eine auf einem Geoinformationssystem (GIS) basierte Multi-Kriterien-Analyse zeigt, dass mehr als 30% des Landes für die Anwendung der MAR-Versickerungsmethode gut oder sehr gut geeignet sind. MAR kann u.a. eine vielversprechende und vielseitige Technologie sein, um den Grundwasserspiegel wiederherzustellen, Grundwasserleiter als Wasserpuffer zwischen Zeiten von Dargebot und Bedarf zu nutzen oder die Wasserqualität zu verbessern. Durch die Diskussion der Anwendbarkeit von MAR am Lake Arenal und im Paacume-Projekt – in beiden Fällen treten große Herausforderungen an der Schnittstelle von Wasser, Energie und Nahrung auf – wird die Notwendigkeit eines WEF-Nexus Ansatz aufgezeigt.

Um zu verstehen, was das Konzept des WEF-Nexus ausmacht, bietet die Dissertation konzeptionelle Analysen zum WEF-Nexus auf der Grundlage einer systematischen Literaturrecherche von 73 konzeptionellen wissenschaftlichen Artikeln aus den letzten zwei Jahrzehnten. Die Analyse zeigt, dass der WEF-Nexus auf bereits bestehenden integrierten Ansätzen aufbaut, jedoch mit dem Ziel, von der Integration in den Sektoren zu einer sektorübergreifenden Integration überzugehen sowie die Politikkohärenz zu verbessern. Die Ergebnisse bestätigen zudem, dass es weiterhin keine allgemein anerkannte Definition des WEF-Nexus gibt. Zudem bietet die Dissertation einen Überblick über 32 verschiedene Nexus Konzepte, etwa ein Dutzend Hauptmerkmale des WEF-Nexus und bis zu 21 verschiedene Aspekte, die im WEF-Nexus integriert werden könnten. Beispiele für Merkmale sind Interdisziplinarität, Transdisziplinarität oder die Ermöglichung der Beteiligung und Einbeziehung von Interessengruppen. Zu den neuen

Merkmalen eines WEF-Nexus gehören ferner die Entwicklung von Nexus-Indikatoren, die Einbeziehung der politischen und sozialen Dimension sowie ein Fokus auf Innovation.

Um den WEF-Nexus anzuwenden, ist ein detailliertes Verständnis der vielen individuellen Verflechtungen zwischen den Bereichen Wasser, Energie und Ernährung erforderlich. Eine solche detaillierte Analyse wird in der Dissertation durch Berechnungen an der Schnittstelle von Wasser und Elektrizität mit unterjähriger Auflösung während der hochdynamischen COVID-19-Pandemie geliefert. Während der Lockdown-Maßnahmen in Europa war der Wasserfußabdruck der thermischen Stromerzeugung im Vergleich zum gleichen Zeitraum vorangegangener Jahre um 21% abgesenkt. Grund dafür sind drei Faktoren: eine mittelfristige Veränderung im Strommix in den Jahren vor der Pandemie hin zu einer weniger wasserintensiven Stromerzeugung sowie – während der Lockdowns – eine kurzfristige Veränderung hin zu einer weniger wasserintensiven Stromerzeugung und ein Rückgang der Stromproduktion im Allgemeinen. Die Analyse zeigt außerdem die Veränderungen im Handel von virtuellem Wasser in fünf europäischen Ländern durch die Verschiebung von Elektrizitätsimporten und -exporten.

Auf der Grundlage der Methodik dieser Analyse wurde die Datenverfügbarkeit bewertet, um ein Instrument zu skizzieren, mit dem der Wasserfußabdruck und der virtuelle Wasserhandel in Europa nahezu in Echtzeit überwacht werden könnte. Ein solches Instrument könnte im Rahmen des WEF-Nexus eingesetzt werden, um das Bewusstsein für den Wasserverbrauch bei der Stromerzeugung zu schärfen, private Akteure zu incentivieren, ihren Wasserfußabdruck zu verringern, und Anreize auf dem Strommarkt zu schaffen, um die Wasserintensität bei der Stromerzeugung z.B. durch Preismechanismen zu reduzieren.

Durch diese Ergebnisse trägt die Dissertation zur konzeptionellen und praktischen Weiterentwicklung des WEF-Nexus bei, um so die Herausforderungen an den Schnittstellen von Wasser, Energie und Nahrung besser zu bewältigen und dadurch die nachhaltige Entwicklung in Costa Rica, Europa und darüber hinaus zu unterstützen.

List of Publications for this Dissertation

Publication 1

Bonilla Valverde, J., Blank, C., **Roidt, M**., Schneider, L., & Stefan, C. (2016). Application of a GIS Multi-Criteria Decision Analysis for the Identification of Intrinsic Suitable Sites in Costa Rica for the Application of Managed Aquifer Recharge (MAR) through Spreading Methods. *Water*, 8, Article 391. https://doi.org/10.3390/w8090391

Type: peer-reviewed article | **Status**: published | **Authorship**: co-author | **Citations***: 90

Author contributions: J. P. Bonilla Valverde conceived and designed the general paper concept, analyzed the results, and wrote the first draft of the paper. C. Blank, **M. Roidt** and L. Schneider processed the thematic layers and contributed to writing the introduction, materials and methods. **M. Roidt** provided additional revisions to the manuscript. C. Stefan contributed to the study's conceptualization and revised and provided feedback on the manuscript.

Short summary: The article presents the first assessment to identify suitable sites for implementing Managed Aquifer Recharge (MAR) spreading methods in Costa Rica. Suitable sites are identified through a GIS multi-criteria decision analysis based on the four criteria: hydrogeological aptitude, terrain slope, topsoil texture and drainage network density. The results indicate that roughly 30% of the country is highly or very highly suitable for closer investigation of MAR-type spreading methods. This map is a tool for the future implementation of MAR techniques in the country.

Integration into the dissertation: The study forms the basis for Part A.

* September 2025 in Google Scholar. That applies to all subsequent publications.

Publication 2

Avellán, T., **Roidt, M.**, Emmer, A., von Koerber, J., Schneider, P., & Raber, W. (2017). Making the Water–Soil–Waste Nexus Work: Framing the Boundaries of Resource Flows. *Sustainability*, 9, Article 1881. https://doi.org/10.3390/su9101881

Type: peer-reviewed article| **Status**: published | **Authorship**: first author* | **Citations**: 52

Author contributions: The concept of the article and the Water-Soil-Waste (WSW) Nexus System was developed by **M. Roidt** and T. Avellán in close collaboration with A. Emmer and the other co-authors. The introduction was written by **M. Roidt**, T. Avellán, and P. Schneider. Sections 2 and 3 were written by **M. Roidt** (apart from section 2.5, which was provided by T. Avellán). Section 4 was written by **M. Roidt** and T. Avellán. A. Emmer contributed the case study in section 5.1. J. von Koerber, P. Schneider and W. Raber provided the case study in section 5.2. **M. Roidt** and T. Avellán wrote section 6. All authors reviewed the manuscript.

***M. Roidt** and T. Avellán contributed equally to this work and are considered co-first authors.

Short summary: In this article, we analyzed integrated management systems and how their system boundaries are defined. We determined that system boundaries should be clear, wide and flexible for them to be applicable. Based on this, we propose the boundary of the WSW-Nexus system. We use two case studies to exemplify the usefulness of these system boundaries.

Integration into the dissertation: The article is part of the work done in Part B. It is referenced in the questions on the boundary of the Nexus. Furthermore, it feeds into Chapter 3.3.1 on holism and reductionism.

Publication 3

Roidt, M., Avellán, T., Seegert, J., & Krebs, P. (2017). *How will Environmental Systems Analysis Inform the Water-Soil-Waste Nexus in 2050 to Support Sustainable Development?* [Conference session]. International Conference on Sustainable Development, Columbia University, New York City, USA.

Type: conference presentation | **Status**: presented | **Authorship**: first author, presenter

Author contributions: T. Avellán and **M. Roidt** designed the research and developed the abstract and presentation. **M. Roidt** compiled the data, performed the analysis, prepared the presentation and presented the results. T. Avellán, J. Seegert, P. Krebs supervised the research. All authors reviewed the presentation.

Short summary: This presentation compares Integrated Water Resources Management (IWRM), Integrated Natural Resources Management (INRM), and Integrated Solid Waste Management (ISWM) to assess how environmental modelling supports the WSW-Nexus. Using a literature review and bibliometric analysis of 350 models, it identifies key physical interlinkages, dominant models, and modelling gaps. Results show sector-specific tools with little cross-application. Three 2050 visions are proposed: combining holistic and reductionist knowledge, focusing on key interlinkages, and developing clear WSW indicators to improve decision-making for sustainable development.

Integration into the dissertation: The presentation is part of the work done in Part B. Due to its focus on the WSW-Nexus and modelling approaches it is only briefly referenced in Chapter 3.3.1.3.

Publication 4

Roidt, M., & Avellán, T. (2019). Learning from Integrated Management Approaches to Implement the Nexus. *Journal of Environmental Management*, 237, 609–616. https://doi.org/10.1016/j.jenvman.2019.02.106

Type: peer-reviewed article | **Status**: published | **Authorship**: first author | **Citations**: 79

Author contributions: M. Roidt and T. Avellán designed the research and developed the paper. **M. Roidt** compiled the data, performed the analysis and wrote the paper. T. Avellán supervised the research. Both authors reviewed the manuscript.

Short summary: This paper assesses i) the intended goals and features of three Integrated Management Approaches (INRM, IWRM and ISWM) and two Nexus Approaches (WEF-Nexus and WSW-Nexus), and ii) how target systems and their integration are viewed in each of the Integrated Management Approaches. The results show that in terms of goals, the Nexus Approaches are very similar to Integrated Management Approaches, with the addition of clearly wanting to address governance and policy aspects, e.g., in the WEF-Nexus. Nexus Approaches try to move away from a single-resource-centric view (e.g., WSW Nexus) and intend to go beyond resources towards sectors (e.g., WEF-Nexus).

Integration into the dissertation: The analysis forms the basis for Part B. It provides the methodology for the first literature research phase (Chapter 3.3.1), which is then extended in Chapter 3.3.2 to the WEF-Nexus in a second literature research phase.

Publication 5

Avellán, T., & **Roidt, M.** (2022). The nexus: Concepts and Frameworks. In F. Brouwer (Ed.), *Handbook on the Water-Energy-Food Nexus* (pp. 16–35). Edward Elgar Publishing. https://doi.org/10.4337/9781839100550.00007

Type: book chapter (submitted in 2020) | **Status**: published | **Authorship**: co-author | **Citations**: 2

Author contributions: T. Avellán developed the paper and wrote the chapter. **M. Roidt** contributed to the manuscript. Both authors reviewed the manuscript.

Short summary: This chapter traces the evolution of the WEF-Nexus, linking it to earlier Integrated Management Approaches, e.g., IWRM. It reviews diverse interpretations, project definitions, and methodological tools, highlighting vagueness, scale-setting, and integration challenges.

Integration into the dissertation: The book chapter provides basic insights into the WEF-Nexus. It provides the history of the Nexus in the introduction of Part B.

Publication 6

Roidt, M., Chini, C. M., Stillwell, A. S., & Cominola, A. (2020). Unlocking the Impacts of COVID-19 Lockdowns: Changes in Thermal Electricity Generation Water Footprint and Virtual Water Trade in Europe. *Environmental Science & Technology Letters*, 7(9), 683–689. https://doi.org/10.1021/acs.estlett.0c00381

Type: peer-reviewed article| **Status**: published | **Authorship**: first author | **Citations**: 60

Author contributions: M. Roidt, A. Cominola, C. M. Chini, and A. S. Stillwell designed the research and developed the paper. **M. Roidt** compiled the data, performed the analysis and wrote the paper. **M. Roidt** and A. Cominola designed the visual elements of the paper. A. Cominola., C. M. Chini, and A. S. Stillwell supervised the research. All authors reviewed the manuscript.

Short summary: We investigated the sensitivity of the electricity-water nexus in the European electric grid to large-scale behavior changes during the COVID-19 pandemic lockdown-like measures. We quantified changes in the virtual water trade between five European countries heavily affected by COVID-19 during the same period. These findings improve understanding of the impacts of large-scale behavior and technological changes on the European electricity-water nexus.

Integration into the dissertation: The study forms the basis for Part C. It further shows how the data and methods can contribute to a tool in a WEF-Nexus Framework.

Publication 7

Chini, C. M., Cominola, A., **Roidt, M.**, & Stillwell, A. S. (2020). *Picking up Steam During the Lockdown? Europe's Thermoelectric Water Footprint During the COVID-19 Pandemic*. [Poster presentation]. American Geophysical Union, Fall Meeting 2020, Online, USA.

Type: conference presentation| **Status**: presented | **Authorship**: co-author

Author contributions: See publication 6. Presentation by C. M. Chini.

Short summary: Presentation of publication 6 at the AGU Fall Meeting 2020.

Integration into the dissertation: See publication 6.

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Publication 8

Roidt, M., Chini, C. M., Stillwell, A. S., & Cominola, A. (2020). *Too Many Data – too Little Data. How Data Reporting Needs to Change to Reliably Calculate Electricity-related Virtual Water in Europe.* [Conference session]. 10th International Congress on Environmental Modelling and Software (iEMSs 2020), Brussels, Belgium.

Type: conference presentation | **Status**: presented | **Authorship**: first author, presenter

Author contributions: M. Roidt and A. Cominola conceived and designed the research. **M. Roidt** carried out the analysis, prepared the presentation and presented the study. C. M. Chini, A. S. Stillwell and A. Cominola provided feedback and supervised the analysis.

Short summary: This presentation investigated the challenges of accurately calculating electricity-related virtual water trade in Europe. Using high-resolution ENTSO-E and JRC datasets, we analyzed electricity generation, trade, and virtual water at sub-basin and country scales, highlighting inconsistencies and data gaps that prevent integrated multi-scale assessments. Results demonstrate the potential of detailed temporal data while underscoring the need for improved reporting standards and harmonized datasets to enhance the reliability of virtual water estimates, thereby supporting informed water-energy nexus management strategies.

Integration into the dissertation: This analysis is part of Chapter 5 and in the discussion of a tool on the water–electricity nexus.

Preface

This dissertation is the result of ten years of research on the Nexus Approach, which I conducted alongside my graduate studies in Hydro Science and Engineering at TU Dresden and my professional career thereafter.

Understanding the suitability of Costa Rica for Managed Aquifer Recharge was part of a research project at TU Dresden. The conceptual research on the Nexus Approach started during my stay at UNU-FLORES, where I worked on my master's thesis. During my professional career, my research continued by aiming to understand the water-energy nexus of the European electricity grid.

This research was conducted as a private endeavor based on publicly available data. It is not directly connected to my professional work. Nevertheless, my thinking and understanding of the Nexus were enriched through the different insights into the water sector I had in my professional career. They are described in the following.

As a Project Engineer at Dorsch International Consultants GmbH, I focused, among other things, on how water supply systems in Jordan and Kosovo can reduce their immense energy use through infrastructure and operational optimization.

As Consultant to the United Nations Economic Commission for Europe (UNECE), I supported the Secretariat of the Water Convention in synthesizing the *Methodology to assess the Water-Energy-Food-Ecosystems Nexus* in transboundary basins.

In my annual lecture on *The Energy Sector and Hydropower at the University of Applied Sciences Rottenburg,* I unravel with the students the vast interlinkages between the water, energy, and food sectors and how important the WEF-Nexus is to the students' future work in water resources management.

At KfW Development Bank, I saw the WEF-Nexus through the lens of infrastructure investments in the water sector in Lebanon and how this sector can adapt to a changing climate and support the mitigation of climate change by using solar energy for pumping or transforming to gravity-feed water supply systems without any electricity input at all.

Looking at the conceptual part of the Nexus Approach through research, accompanied by practical implementation and guided by many experienced colleagues and insightful conversations, was an enriching journey that is now compiled in this document.

I want to thank Prof. Dr. Volker Hochschild and Prof. Dr. Heidi Megerle for the encouragement, the advice, and the constructive supervision during the preparation of this dissertation.

Thank you, Urszula and Michèle, for looking after the children. Many hours of your time made it possible for me to put this dissertation together. I am deeply impressed by you two dedicated and loving grandma´s.

Thank you, dear Anna, for providing for the family financially and emotionally during the last year. Thank you for agreeing with me writing this dissertation even if it would not leave much time for the two of us besides my writing, your work and raising the kids. Next time we go to Albania for vacation, I will not sit in the hotel all day writing.

I also want to thank my co-authors for the research we carried out together. I especially want to extend my gratitude to Tamara and Andrea, not only for the joint research we conducted but also for your mentorship and advice over the past years.

Thank you, Jonas and especially André, for proofreading the manuscript. André, your several rounds of feedback, your intelligent sparring and your friendship meant a lot in the final phase of writing.

Thank you, Hannes, for your support in acquiring literature.

Thank you, Marco and Fabrizia, for your hospitality and amazing wild fennel pasta during the final push.

1 Introduction

The systems of water, energy, and food are connected through numerous interlinkages ranging from direct links, such as the need for electricity in groundwater pumping for irrigation, to less obvious relations, such as river depth maintenance to ensure waterway transport of coal to produce electricity. Such linkages occur at all levels, ranging from the household level through energy and water demand for food preparation to the global trade of food commodities produced using water and energy. One can summarize this variety of interlinkages into a triangle that shows how the sectors bidirectionally depend on each other (see Figure 1).

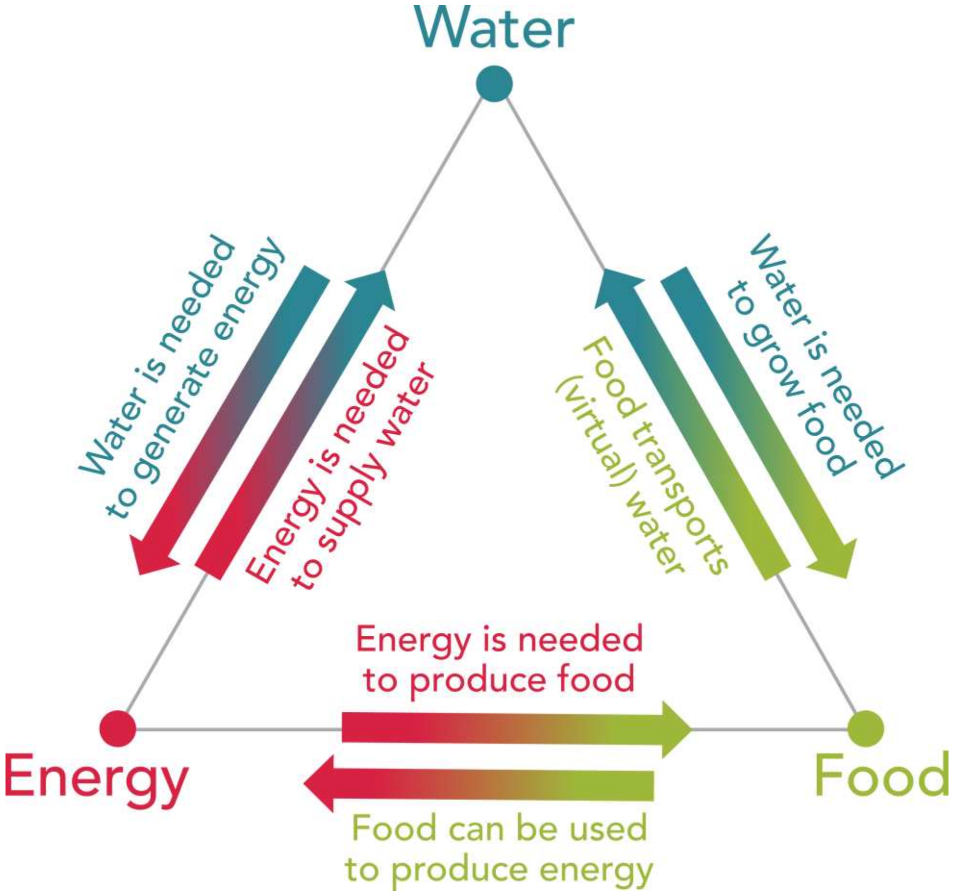


Figure 1: *Interactions between the water, energy, and food sectors. All sectors are related in both ways through multiple interlinkages illustrated with examples. Source: Roidt & Avellán (2019, p. 610), based on UNU-FLORES (the online source is no longer available).*

The world's population rapidly increased in the past decades from less than 6.0 billion people in the 1990s to 8.1 billion in 2024. In the future, it is expected that the global population will increase to 9.7 billion in 2054, with a peak in 2084 at 10.3 billion (UNDESA, 2024). This rise in world population and improved prosperity has put the three sectors under immense pressure, which is increasing.

In the past 50 years, global crop production has tripled (D'Odorico et al., 2018), and in the next decade alone, crop and meat production are expected to grow by another 13% compared to a 2025 baseline (OECD & FAO, 2025). However, the main constraints to agricultural production are the increased scarcity and diminished quality of water resources and land (FAO, 2018). The agricultural sector alone accounts for 72% of water withdrawal (FAO, 2025) and 30% of the world's energy consumption (IRENA, 2015).

In the past years, many regions have experienced increasing water stress, with 18% of the world being considered water-stressed in 2020. Already, currently, half of the global population experiences severe water scarcity at some point in the year (Carretta et al., 2023). At the same time, global water demand is expected to increase 20 – 33% by 2050 compared to a 2010 baseline (IIASA, 2016). Even though municipal water demand accounts for only 13% of global water demand (FAO, 2025), large amounts of energy are required to transport drinking water from source to consumer (IRENA, 2015).

The annual increase in global energy demand is slowing, yet demand is expected to rise by 19% by 2050 compared to a 2023 baseline. The share of electricity demand will rise much more due to the ongoing electrification of the energy sector (IEA, 2024).

Such rising demands for food, energy, water, and land, alongside population increase and climate change, led chief scientific adviser to the UK Government Sir John Beddington to conclude in 2009 that we may face a perfect storm of global events by 2030 (Beddington, 2009).

Several steps have been taken by the global community to prevent this threat, primarily the Sustainable Development Goals (SDGs) to achieve sustainability within several sectors among them the energy, water, and food sectors (United Nations, 2015), the Paris Agreement to mitigate and adapt to climate change (UNFCCC, 2015) and most recently the Kunming-Montreal Global Biodiversity Framework to halt and reverse biodiversity loss (UNEP, 2022).

In this context, Hoff (2011) pointed directly at the interconnectedness of these topics by formulating that "[c]onventional policy- and decision-making in 'silos' … needs to give way to an approach that reduces trade-offs and builds synergies across sectors – a nexus approach. Business as usual is no longer an option" (p. 7). Therefore, recognizing that the water-, food-, and energy sectors depend on each other and tackling them in a joint approach represents the basis of what is now referred to as the Water-Energy-Food Nexus (WEF-Nexus).

The WEF-Nexus aims to reduce trade-offs between sectors and increase synergies among them. By achieving greater policy coherence and higher resource efficiency of water, food, and energy, the WEF-Nexus aims to support the transition to a green economy, the security of water, food, and energy, sustainable and equitable growth and a resilient and productive environment (Hoff, 2011).

While the term Nexus in this context was used before (see Chapter 3.1), the Bonn 2011 Nexus Conference and its Background Paper by Hoff (2011) kick-started research activity in the field. Since then, scientific publications tackling the WEF-Nexus have soared from less than one publication per year before 2011 to more than 300 publications per year in the past five years. This trend is shown in Figure 2 exemplary for peer-reviewed English publications in the Scopus database. More than 3,000 peer-reviewed WEF-Nexus articles have been published (see Chapter 3.2 on the search methodology), and more than 15,000 total publications appear after 2011 when Google Scholar is searched for "Water Energy Food Nexus".

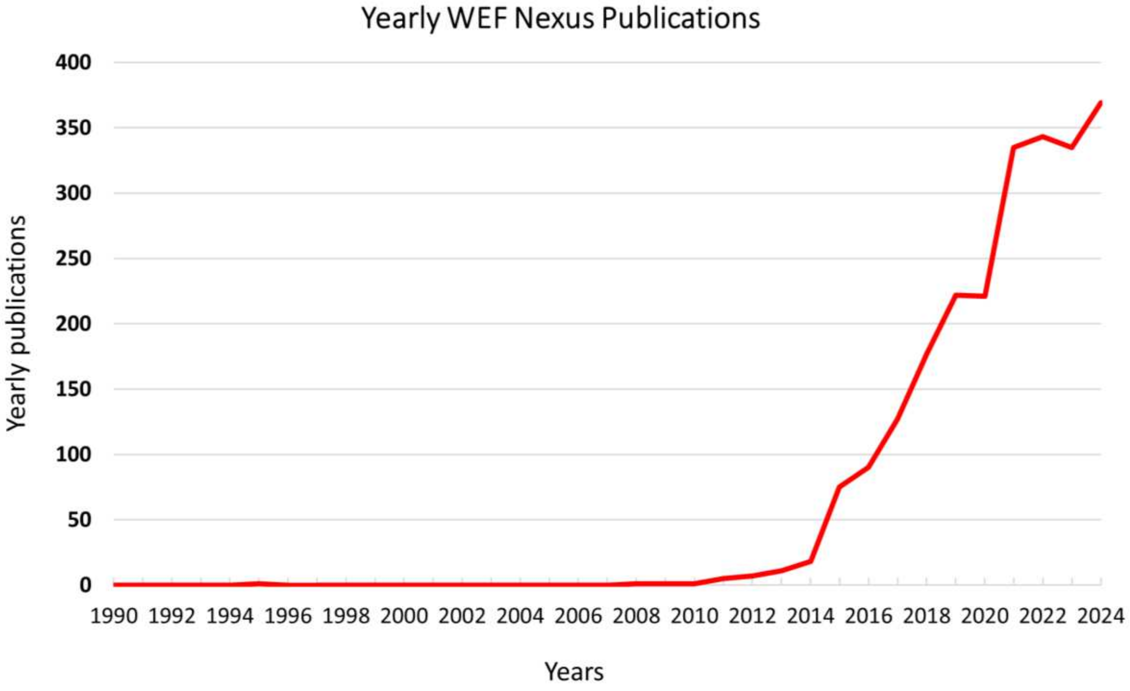


Figure 2: *Graph of WEF-Nexus publications showing the annual (not cumulative) increase in peer-reviewed articles on the WEF-Nexus within the Scopus database between 1990 and 2024. The rate of publications increased from fewer than one publication per year prior to 2011 to more than 300 articles per year after 2020. Source: Own illustration.*

Researchers are investigating the manifold interlinkages between the three sectors and the related policies to produce policy recommendations (Galli et al., 2022; Vrachioli et al., 2023). Large research projects are initiated and funded, such as NEXOGENESIS, REXUS, AWESOME, GoNEXUS, RETOUCHNEXUS or CisWEFE-NEX, under Horizon2020 or HorizonEurope funding (CisWEFE-NEX, 2025; GoNEXUS, 2025; Nexogenesis, 2025; PRIMA, 2025; Retouch Nexus, 2025; REXUS, 2025). Case studies are implemented across scales, for instance, participatory modelling for WEF governance in the Mediterranean (Pagano et al., 2025), WEF footprint assessments in China (Yang et al., 2025), and resource recovery pilot studies in wastewater treatment plants (Bhambhani et al., 2025).

Apart from research, intergovernmental institutions and international networks are working with governments and practitioners in nexus assessments to improve policy coherence and increase synergies among the sectors. Examples are the United Nations Economic Commission for Europe (UNECE) as summarized in Roidt & de Strasser (2018), the UN Food and Agriculture Organization (FAO) in FAO (2014) or the Global Water Partnership (GWP) in the WEFE4MED project (GWP-MED, 2025).

Common to all this work is the claim to apply a Nexus Approach mainly to water, energy, food, and ecosystems, but also to other resources and sectors. However, the discussion on what a WEF-Nexus Approach exactly is was not yet conclusively clarified (Jones-Crank, 2025). “[C]onceptual confusion” on the WEF-Nexus still remains (Eriksson et al., 2025, p. 10). The most compelling evidence of this is that there is no commonly agreed-upon definition of what a WEF-Nexus approach is (see Chapter 3.3). The fact that conceptual research is very recently still being published (see Table 3 in Chapter 3.2) suggests that the scholarly debate on the WEF-Nexus is still ongoing. On the one hand, the Nexus is described as an important paradigm to support sustainable development and the SDGs (Biggs et al., 2015) and on the other hand, critical voices question if the Nexus is merely a buzzword (Cairns & Krzywoszynska, 2016) or is used to access funding by rebranding old ideas (Proctor et al., 2021).

With WEF-Nexus challenges at all scales and many contexts a WEF-Nexus Approach cannot be described as a recipe (Simpson & Jewitt, 2019b). Further, Sušnik & Staddon (2022) argue that there cannot be a one-size-fits-all approach in the Nexus and that a single approach for all studies that tackle the WEF-Nexus problems is unlikely.

In this dissertation, however, the assumption prevails that the WEF-Nexus Approach must be coined into a tangible *WEF-Nexus Framework* that provides guidance on its application and brings clarity on what is part of it and what is not. If a WEF-Nexus Framework is to become a long standing, effective concept, we must develop a clear understanding of it. On the one hand it must be wide and flexible enough to address the multitude of challenges at the interfaces of water, energy, and food in different contexts. On the other hand, the concept cannot fray out into a generic all-encompassing notion. If every assessment, each infrastructure project, all research initiatives, or every policy analysis that concerns the nexus of water, energy, and food claims to apply a WEF-Nexus Framework, the concept risks being rendered meaningless.

The process of describing such a WEF-Nexus Framework can be seen as a large puzzle that has been forming for more than a decade. This dissertation aims to provide a few small pieces to that puzzle by providing theoretical and practical research.

It does so threefold. First, by looking at Managed Aquifer Recharge (MAR) as a water resources management tool within the WEF-Nexus based on our research in 2016. It then goes on to investigate the WEF-Nexus from a theoretical, historical, and conceptual perspective based on our research in the years 2017 – 2020. Lastly, a practical example of computing interlinkages within the WEF-Nexus is provided based on our investigations in 2020.

The dissertation is divided into three parts. Figure 3 gives an overview of these parts and how the publications as basis of this dissertation contribute to each part.

Part A – Considerations of MAR – looks at MAR in Costa Rica, providing an overview of the physical suitability of the country to apply it. Furthermore, the question is whether MAR is suitable to tackle major challenges within the nexus of water, energy, and food. Hence, the overall objective of this part is the question:

- **Can MAR tackle water, energy, and food challenges?**

This overarching question is discussed based on a case study in Costa Rica. More detailed specific objectives under this overall question are shown in Chapter 2.1.4.

Part B – Conceptual Analyses – focuses on what exactly is understood by the WEF-Nexus. It focuses specifically on the following research question:

- **What constitutes the WEF-Nexus?**

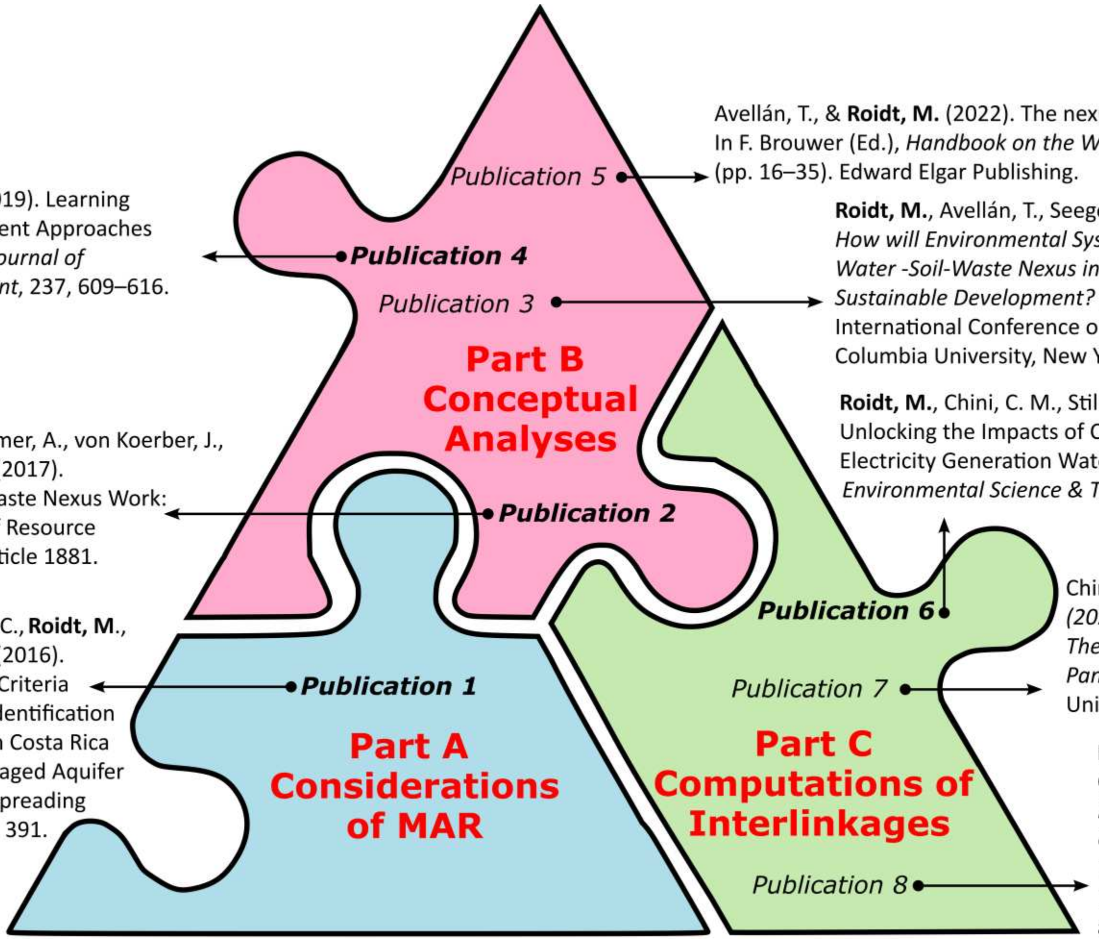
More detailed, specific objectives under this overarching question are shown in Chapter 3.1.3.

Part C – Computations of Interlinkages – contributes calculations of the water footprint and virtual water trade in Europe at the sub-annual scale and an outline for a tool within a WEF-Nexus Framework. Therefore, the objective of

- **Provide the computation of interlinkages at the nexus of water and electricity in Europe.**

More detailed, specific objectives under this overarching objective are shown in Chapter 4.1.3.

Each part will include separate specific chapters on introduction, methodology, results, and discussion. At the end, an overall discussion, outlook, and conclusion is presented.



Avellán, T., & **Roidt, M.** (2022). The nexus: Concepts and Frameworks. In F. Brouwer (Ed.), *Handbook on the Water-Energy-Food Nexus* (pp. 16–35). Edward Elgar Publishing.

Roidt, M., & Avellán, T. (2019). Learning from Integrated Management Approaches to Implement the Nexus. *Journal of Environmental Management*, 237, 609–616.

Roidt, M., Avellán, T., Seegert, J., & Krebs, P. (2017). *How will Environmental Systems Analysis Inform the Water -Soil-Waste Nexus in 2050 to Support Sustainable Development?* [Conference session]. International Conference on Sustainable Development, Columbia University, New York City, USA.

Avellán, T., **Roidt, M.**, Emmer, A., von Koerber, J., Schneider, P., & Raber, W. (2017). Making the Water–Soil–Waste Nexus Work: Framing the Boundaries of Resource Flows. *Sustainability*, 9, Article 1881.

Roidt, M., Chini, C. M., Stillwell, A. S., & Cominola, A. (2020). Unlocking the Impacts of COVID-19 Lockdowns: Changes in Thermal Electricity Generation Water Footprint and Virtual Water Trade in Europe. *Environmental Science & Technology Letters, 7(9), 683-689.*

Chini, C. M., Cominola, A., **Roidt, M.**, & Stillwell, A. S. *(2020). Picking up Steam During the Lockdown? Europe's Thermoelectric Water Footprint During the COVID-19 Pandemic*. [Poster presentation]. American Geophysical Union, Fall Meeting 2020, Online, USA.

Bonilla Valverde, J., Blank, C., **Roidt, M.**, Schneider, L., & Stefan, C. (2016). Application of a GIS Multi-Criteria Decision Analysis for the Identification of Intrinsic Suitable Sites in Costa Rica for the Application of Managed Aquifer Recharge (MAR) through Spreading Methods. *Water*, 8, Article 391.

Roidt, M., Chini, C. M., Stillwell, A. S., & Cominola, A. (2020). *Too Many Data – too Little data. How Data Reporting Needs to Change to Reliably Calculate Electricity-related Virtual Water in Europe.*[Conference session]. 10th International Congress on Environmental Modelling and Software (iEMSs 2020), Brussels, Belgium.

Figure 3: *Representation of the structure of the dissertation divided into three parts. The publications relevant to this dissertation are shown and allocated to one of the parts. The figure shows a chronicle throughout time. Part A was developed first in 2016, and second, Part B was elaborated in publications mainly between 2017 and 2020 (the last publication was published in 2022; however, it was submitted in 2020). Part C shows the latest publications in 2020. Publications marked in bold are peer-reviewed. Source: Own illustration.*

2 Part A – Considerations of Managed Aquifer Recharge

2.1 Introduction

Sustainable water resources management requires a bundle of diverse technologies and methods to produce raw water, improve water quality, store it and distribute it to the end user in either domestic homes, industry or agriculture. The SDGs prominently feature the water sector with the goal to "[e]nsure availability and sustainable management of water and sanitation for all" until 2030 (United Nations, 2015, p. 18).

That this goal is not reached (UNDESA, 2025) shows that water management has great challenges ahead. Furthermore, climate change is heavily impacting water resources management through increased rainfall intensity, risk of flooding, increased frequency and severity of droughts, sea level rise and desertification in some areas (Carretta et al., 2023; Mirzabaev et al., 2022).

One technology that can be applied in several settings is Managed Aquifer Recharge (MAR), as it provides solutions to support access to drinking water and to adapt to a changing climate at the same time. Water from the rainy season can be stored for dry periods, overexploited groundwater can be recharged, or water quality improved through ground filtration. MAR is a technology that benefits water resources management at the stages of water production, improvement of water quality and storage of water as described in more detail below.

2.1.1 State of the Art in Managed Aquifer Recharge

"Managed aquifer recharge is the intentional recharge of water to aquifers for subsequent recovery or environmental benefit", is the definition of MAR that Dillon et al. (2019, p. 3) use in their highly cited article *Sixty Years of Global Progress in Managed Aquifer Recharge.* The definition is also used in other recent articles (Page et al., 2023; H. Zhang et al., 2020). The term combines different technologies that share a common goal: to ensure that, through artificial recharge, more water infiltrates into groundwater aquifers than would naturally occur (Bonilla Valverde et al., 2018). This became an important instrument for managing aquifers with high abstraction rates and depleting groundwater levels due to overextraction (Dillon et al., 2019). MAR is, however, also used as a nature-based solution in raw water treatment (e.g., in river bank filtration (IGRAC, 2024)), as emergency water storage for the city of Abu Dhabi (Kalbus et al., 2019), as buffer storage in a seasonal setting or as an adaptation strategy to increasing intensity of climate extremes (Dillon et al., 2019). It is thus one component in ensuring water security in many different settings, but especially in (semi)-arid regions (H. Zhang et al., 2020).

The objectives of MAR are manifold. In a recent literature review, Sufyan et al. (2024) give an updated overview of the objectives:

- **Water Resources Management:** Restoring groundwater levels or using aquifers as a buffer between supply and demand.
- **Water Quality Improvement:** Improving water quality in aquifers.
- **Natural Treatment of Wastewater:** Treating wastewater as a nature-based solution.
- **Prevent Seawater Intrusion:** Preventing seawater from entering aquifers by increasing groundwater levels.
- **Retain Excess Rainwater:** Storing rainwater in aquifers.
- **Reduce Land Subsidence:** Reduce the subsidence of land caused by aquifer overexploitation.
- **Adaptation to Climate Change:** Most of the above methods are increasingly necessary due to climate change, i.e., increased rainfall intensity and change in rainfall patterns, rising sea levels, higher demand for drinking water and higher need for using aquifers as buffers.

(Sufyan et al., 2024)

Several methods exist to artificially recharge an aquifer, categorized into five major categories commonly used (Bonilla Valverde et al., 2018; Dillon et al., 2019; Sufyan et al., 2024; H. Zhang et al., 2020). These are:

- **Spreading Methods:** Using larger water-filled areas such as ponds, spreading basins or constructed wetlands, allowing water to infiltrate to an unconfined aquifer.
- **In-channel Modifications:** Dams above or below the ground mostly in ephemeral streams detaining (flood) water and allowing for infiltration to an unconfined aquifer.
- **Well, Shaft and Borehole Recharge:** Injection of water through a well to also allow recharge of deeper, or confined aquifers.
- **Induced Bank Filtration:** Extracting groundwater connected to rivers, allowing river water to pass to the groundwater for subsequent extraction.
- **Run-off/Rainwater Harvesting:** Small-scale MAR where (roof) collected rainwater is allowed to infiltrate to the ground from pits, trenches or wells.

(Dillon et al., 2022)

Different sources of water are used for MAR, whereby the lion's share is river water with 52%, mainly through induced river bank filtration projects in Europe (especially Germany and the Netherlands) (Sprenger et al., 2017). Other sources are storm water (18%), reclaimed wastewater (8%), groundwater (8%), lake water (7%) and other minor sources (IGRAC, 2024).

MAR research and implementation have consistently grown and matured over the last 65 years. It has now reached roughly 1% of global groundwater extraction and is expected to exceed 10% of global extraction in the future (Dillon et al., 2019). The global MAR portal shows till date a total of 1,200 larger sites where MAR is (or was) implemented. (IGRAC, 2024) (This does not include rooftop or private groundwater infiltration). Implementation is highest in Europe with 37%, followed by Asia (31%) and North America (19%) and is significantly lower in Oceania (7%), Africa (5%), and South America, with only 1% of global distribution (Seidl et al., 2024). While the data from Seidl et al. are generally consistent with the MAR Portal, they differ for South America, where the MAR Portal shows 10% of global distribution (IGRAC, 2024).

Till today, research on MAR has been ongoing as it is further refined and developed. The focus lies both on the quantitative aspects in water resources management, but also on how several water quality parameters can be improved (Sufyan et al., 2024). Generally, however, the technical implementation side of MAR has been well developed and understood. This is shown e.g., in the standard textbook *Managed Aquifer Recharge: Overview and Governance*, published by the International Association of Hydrogeologists (IAH) (Dillon et al., 2022), the Standard Guidelines for Managed Aquifer Recharge by the American Society of Civil Engineers (2020) or the several other regulations and guidelines on MAR from Australia, Chile, India, Italy, Mexico, Portugal, South Africa, Spain, Netherlands, and USA as compiled by Escalante et al. (2020).

In a comprehensive review, it is concluded that a “sophisticated hydrogeological understanding of the MAR recharge site and management of associated operational risks are important determinants for scheme success“ (Seidl et al., 2024, p. 10). However, prior to detailed hydrogeological investigations and operational considerations, it is suggested to get a general overview of a region to gain insights into where MAR could generally be suitable from a physical perspective by using available data, GIS and remote sensing tools. This will ensure a cheap, fast, and straightforward understanding of whether more detailed investigations are meaningful. To achieve this, MAR suitability mapping is carried out and is also the focus of our work in Bonilla Valverde et al. (2016).

2.1.2 State of the Art of MAR Suitability Mapping

To find suitable sites for MAR, projects with remote sensing and GIS techniques have been applied in the past two decades and research is still ongoing in many regions of the world e.g., India: (Bhuiyan, 2015; Chowdhury et al., 2010; Krishnamurthy et al., 1996; Patil & Mohite, 2014; Ravi Shankar & Mohan, 2005; Saraf & Choudhury, 1998; Singh et al., 2013; Sukumar & Sankar, 2010); Iran: (Ghayoumian et al., 2007; Mehrabi et al., 2012; Saravi et al., 2006); Jordan: (Alraggad & Jasem, 2010; Hammouri et al., 2014); Tunisia: (Aloui et al., 2022; Chenini & Ben Mammou, 2010; Kallali et al., 2007); Kazakhstan: (Sallwey et al., 2024); Europe: (Martins et al., 2024; Panagiotou et al., 2024) and Africa: (Ebrahim et al., 2024)

The above-mentioned studies mainly focus on the site selection by using different parameters such as slope, geology, aquifer depth, land use, drainage density, soil texture, geomorphology, lineament density, infiltration rate and others. These input parameters are then processed and overlaid resulting in suitability maps for the areas investigated.

One common aspect of the studies mentioned is that their focus lies on the scale of smaller regions or watersheds. Many of the studies investigate areas below 10,000 km² (Aloui et al., 2022; Chenini & Ben Mammou, 2010; Chowdhury et al., 2010; Ghayoumian et al., 2007; Hammouri et al., 2014; Kallali et al., 2007; Krishnamurthy et al., 1996; Mehrabi et al., 2012; Panagiotou et al., 2024; Patil & Mohite, 2014; Ravi Shankar & Mohan, 2005; Saraf & Choudhury, 1998; Saravi et al., 2006; Singh et al., 2013; Sukumar & Sankar, 2010). Three study areas exceed 10,000 km² (Bhuiyan, 2015; Martins et al., 2024), and two study areas are larger than 2 million km² (Ebrahim et al., 2024; Sallwey et al., 2024)

All articles mentioned above focus on suitability mapping for MAR with similar methodologies. Calculation approaches and input parameters, however, are not the same and not directly and easily comparable. Aiming to harmonize this, the INOWAS Group at TU Dresden developed an easy to use, freely available online tool for MAR suitability mapping on the INOWAS Platform (Glass et al., 2022; Sallwey et al., 2019).

The ongoing studies and the recent online tool show that MAR suitability mapping is a well-established approach to understand, as a first step, if MAR has potential in a region.

2.1.3 Research Deficit

It was our aim to carry out the analysis for the entire country of Costa Rica. Prior to our analysis, no MAR suitability study was found in which a whole nation was investigated. In the years thereafter, however, a study was done for the Republic of Cyprus (Panagiotou et al., 2024) and on a very large scale, for Kazakhstan (Sallwey et al., 2024) and the entire continent of Africa by Ebrahim et al. (2024).

Based on the MAR Portal (IGRAC, 2024), two sites are implemented in Costa Rica using induced river bank filtration, one at the Pacific side in Puntarenas and one at the Caribbean side in Limón (Salguero & Penón, 2006).

Costa Rica is a tropical country with a central mountain system and an abundance of trade winds (Quintero & Flores, 2001), resulting in a very high mean annual rainfall of over 3,300 mm, where more than two-thirds becomes runoff that quickly discharges to the close coasts of the Pacific Ocean or the Caribbean Sea lost for further human use (UNESCO, 2007). In addition, the water is not equally distributed, making it difficult for water managers to ensure a continuous supply.

Especially significant is the dry season with almost no rain for up to four months (Quintero & Flores, 2001) which is coinciding with the touristic season with an increased domestic water demand. To tackle this situation MAR seems like a suitable technology to buffer water from the rainy season to be used in the dry season with increased demand. However, before detailed soil and hydrogeologic investigations can start, general suitability mapping of the country is an important first step in generating a general understanding.

Such a MAR suitability mapping has not been carried out. Hence up until our publication in 2016, there was a gap of a general understanding of MAR suitability in Costa Rica that we contributed to closing.

2.1.4 Objectives

The detailed objective of this part is to carry out a MAR suitability mapping exercise in Costa Rica. The focus lies on the intrinsic physical conditions of spreading methods into unconfined aquifers. The aim is to produce an overview map for the entire country showing MAR suitability.

The results and a general look at the water, energy, and agricultural sectors in Costa Rica will then lead to answering the overall objective of Part A as formulated in Chapter 1 (Can MAR tackle water, energy, and food challenges?).

2.2 Materials and Methods

The analysis was carried out for the entire country of Costa Rica located in Central America between the Caribbean Sea and the Pacific Ocean with a total surface area of 51,100 km² (Salguero et al., 2006). Hence only data that is available for the entire country is used.

A Multi-Criteria Decision Analysis using a Geographic Information System (GIS-MCDA) was carried out based on Rahman et al. (2012). We described this in detail in Bonilla Valverde et al. (2016). We further showed that this method was used in several countries in the past decade to analyze the suitability of MAR.

Before performing the actual analysis, areas that are not suitable for MAR were excluded through a first screening process.

2.2.1 Screening

Locations within protected areas (Republic of Costa Rica, 1995), where MAR is not permitted by local law, as well as wetlands, beaches, and terrain slopes >40% (Republic of Costa Rica, 1996) are considered unsuitable for MAR. Figure 4 shows that 39% of the country is not suitable for MAR at all. This is due to the large, protected areas in Costa Rica, mainly in the Southeast of the country (see Figure 7) and to a lesser degree to the remaining steep terrain outside of protected areas in the central mountain range of the country and on the Nicoya Peninsula (see Figure 6).

The screening revealed that more than 60% of the country is potentially suitable for MAR spreading methods, making the continuation of the analysis worthwhile.

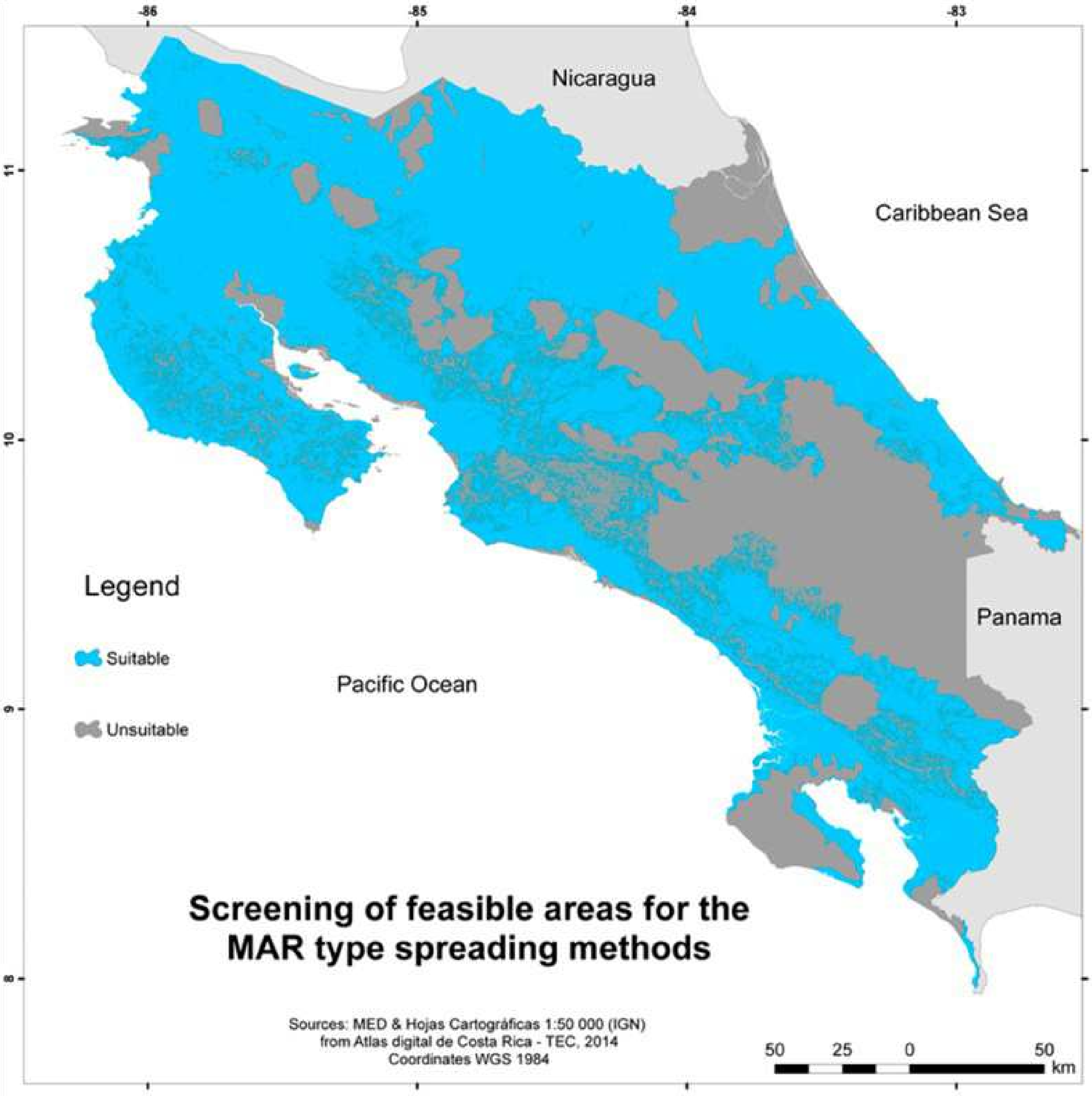


Figure 4: *Map showing the areas in Costa Rica in which MAR-type spreading methods are generally suitable. It excludes areas in which MAR is not permitted (e.g., protected areas) or otherwise not possible (e.g., wetlands or terrain slopes >40%). Blue areas are generally suitable and used for further investigation while gray areas are unsuitable. Source: (Bonilla Valverde et al., 2016, p. 10).*

The following four spatial parameters were used to perform the analysis and are described in the following:

- Hydrogeological aptitude,
- Terrain slope,
- Soil texture,
- Drainage network density.

Hydrogeological aptitude is the characteristic of a geological rock formation that expresses the potential to have an unconfined aquifer that may be used for various human activities (Astorga & Arias, 2003). The parameter is based on the geological map of Costa Rica (Tournon et al., 1997) and categorized into high, moderate, low, and no potential by others (Astorga & Arias, 2003; Bundschuh & Alvarado, 2007; Tournon et al., 1997). See Figure 5.

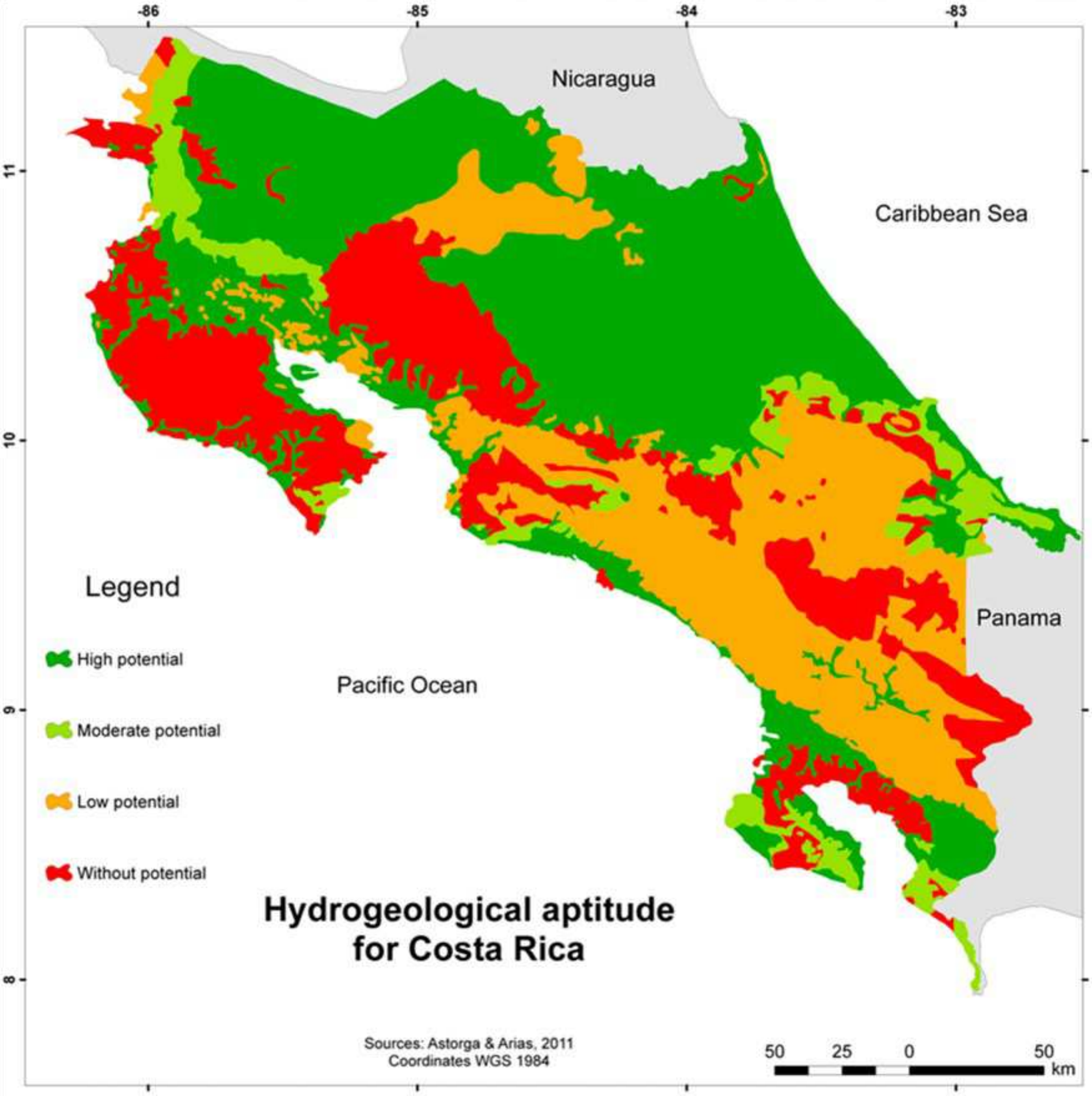


Figure 5: *Map showing Costa Rica's hydrogeological aptitude as one parameter for performing suitability analysis. High and moderate potential is found predominantly in the north, northwest, and along the coasts, while low or no potential dominates the southwest and the east of the country. Source: (Bonilla Valverde et al., 2016, p. 6).*

Terrain slope is an important criterion for natural groundwater recharge in the water balance of a watershed (Rahman et al., 2012). Gentle slopes <5% allow for higher infiltration, and steep slopes have poor groundwater infiltration. The parameter was created using a 30-meter pixel Digital Elevation Model (DEM) from the Costa Rica digital atlas (Instituto Tecnológico de Costa Rica, 2014). See Figure 6.

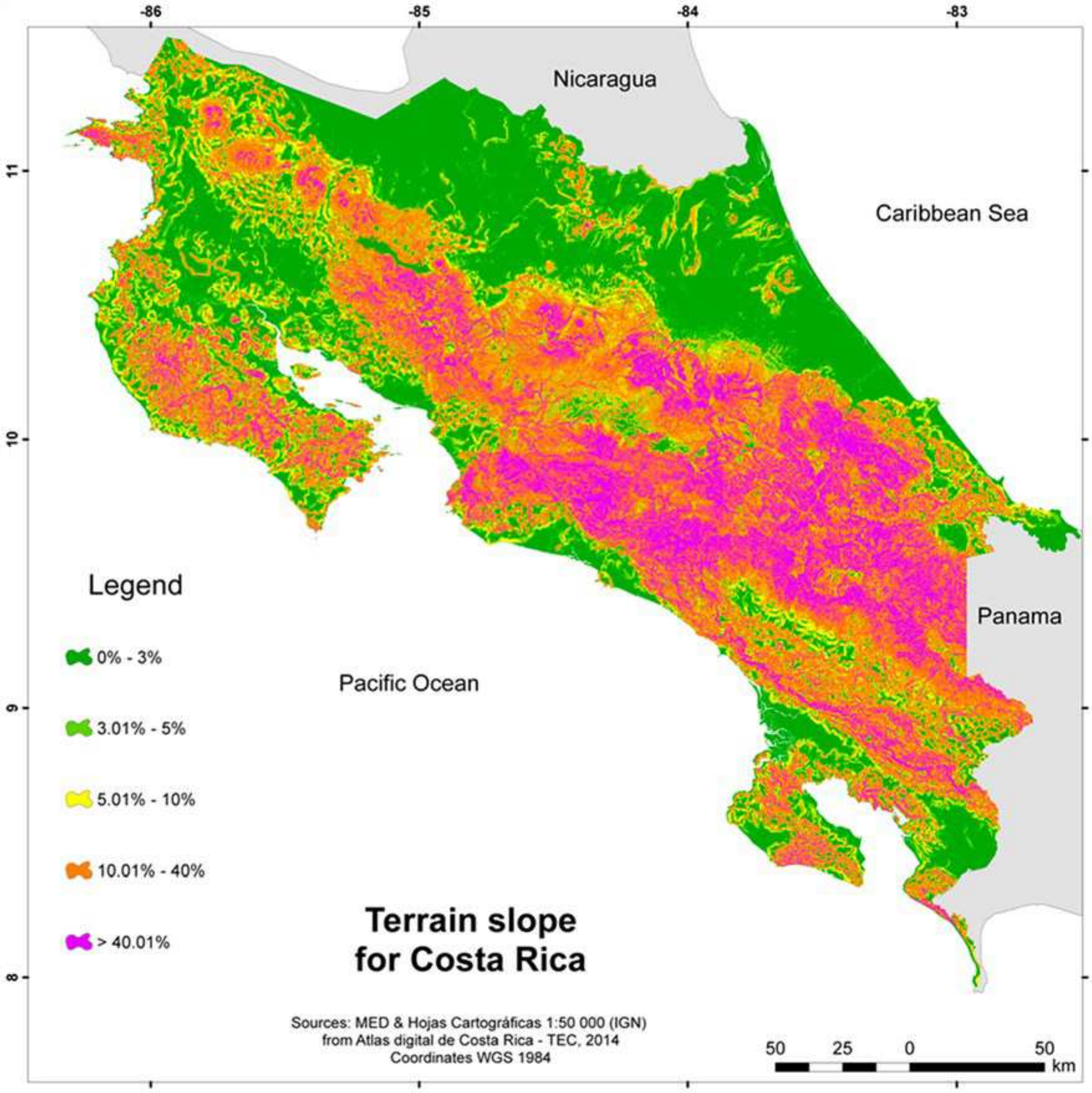


Figure 6: *Map showing the terrain slope of Costa Rica as one parameter for suitability analysis. Steep slopes above 40% dominate the central mountain range while towards both coasts and the north the slopes are below 5%. Source: (Bonilla Valverde et al., 2016, p. 7).*

Top soil texture is the main parameter that influences the soil's capacity to support the infiltration of water into the subsurface (Singh et al., 2013; Sukumar & Sankar, 2010). The higher the clay content in the soil, the lower the permeability (thus inhibiting the infiltration). Therefore, a low clay fraction (<10%) is favourable for infiltration (Kallali et al., 2007). Coarse-texture soils (such as sands), on the other hand, have large pores that facilitate water drainage, in contrast to the fine pores in clay that retard drainage (Dunne & Leopold, 1978). The parameter is created based on data collected by the Ministerio de Agricultura y Ganadería of Costa Rica (MAG) and digitized by the Instituto Tecnológico de Costa Rica (2014). See Figure 7.

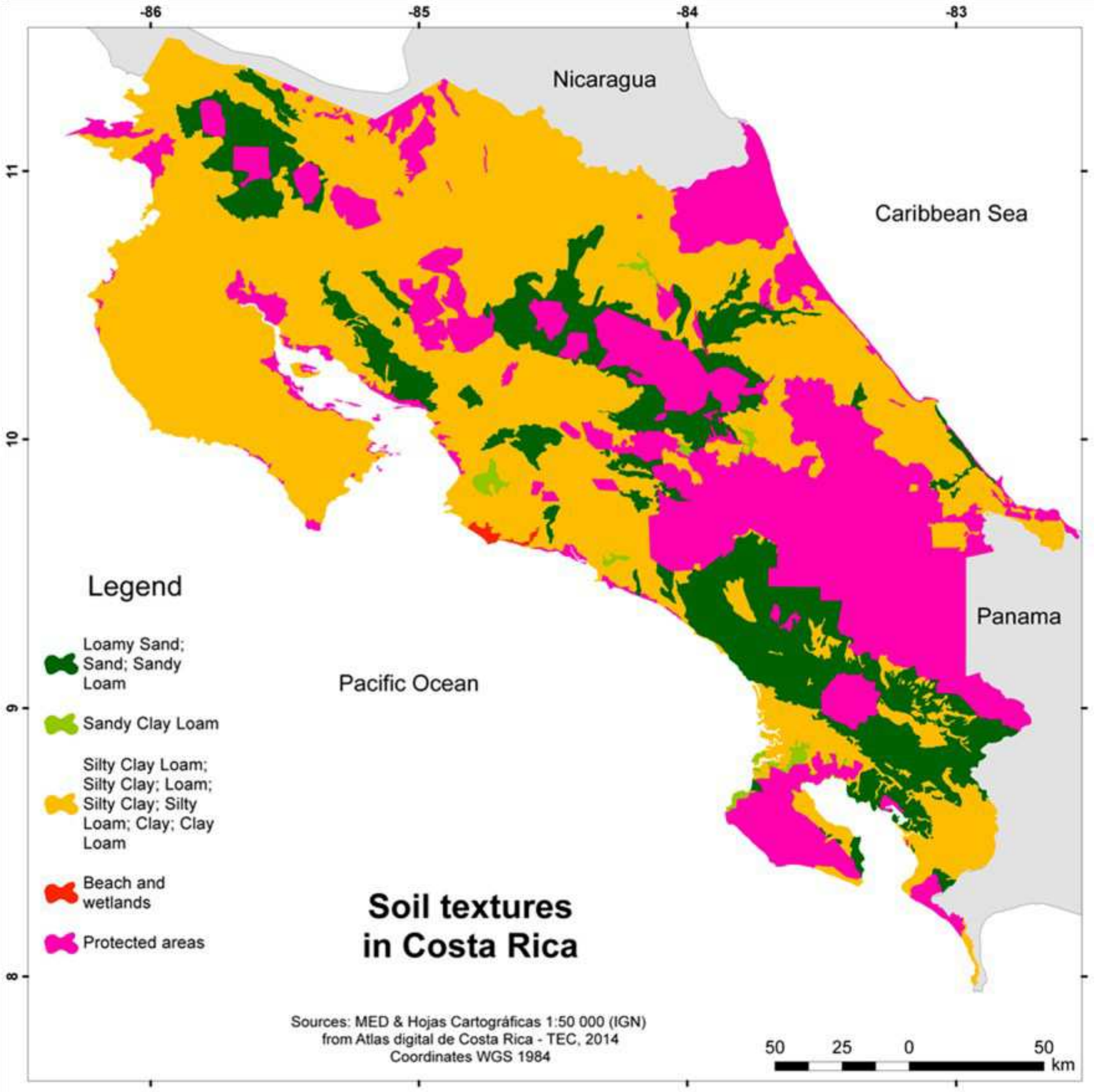


Figure 7: *Map showing the soil texture of Costa Rica as one parameter for the suitability analysis. In most of the country, outside of protected areas, clayey and loamy soils dominate. Source: (Bonilla Valverde et al., 2016, p. 8).*

Drainage network density as an indicator for the natural infiltration of a terrain. Infiltration depends upon surface runoff and permeability (Krishnamurthy et al., 1996). A higher drainage network density reflects a higher runoff, hence less infiltration (Shaban et al., 2006). We calculated the parameter based on the river network of Costa Rica´s National Geographic Institute (IGN, n.d.). See Figure 8.

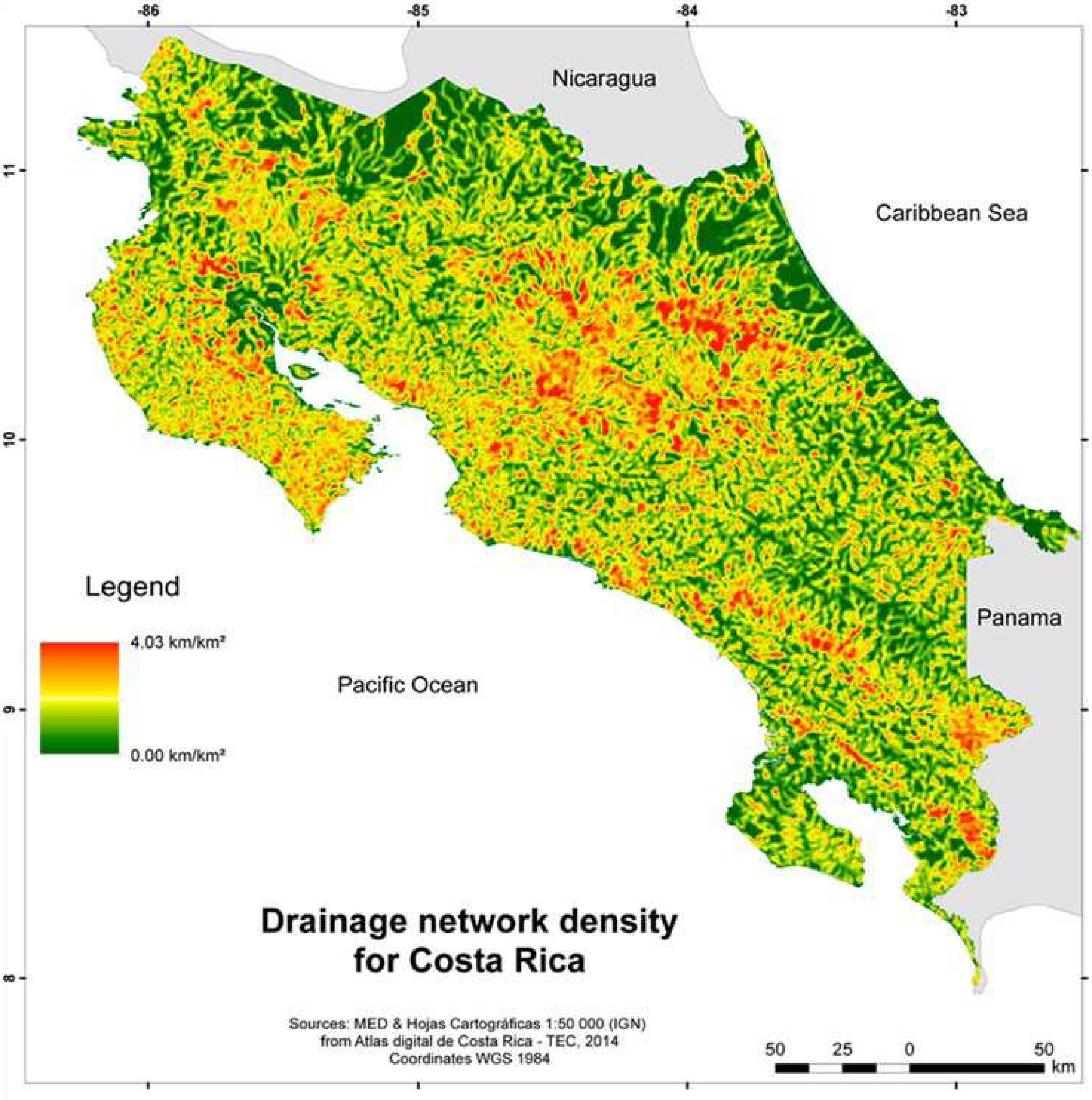


Figure 8: *Map showing the drainage network density of Costa Rica as one parameter to perform suitability analysis. The drainage network density is high in more mountainous and steeper areas representing higher runoff. Source: (Bonilla Valverde et al., 2016, p. 9).*

2.2.2 Suitability Analysis with Standardized and Weighted Parameters

2.2.2.1 Standardization

The calculation of the suitability was carried out based on the Weighted Linear Combination (WLC) method with which parameters are standardized and weighted.

The input parameters are first standardized between 0.0 – 1.0. How exactly the standardization is done plays a major role in the result of the suitability, i.e., which soil texture class is assigned to which standardized value. Hence in Bonilla Valverde et al. (2016) we describe in detail how and why the standardization was carried out based on well researched methods. The standardized values for each parameter are shown in Figure 9.

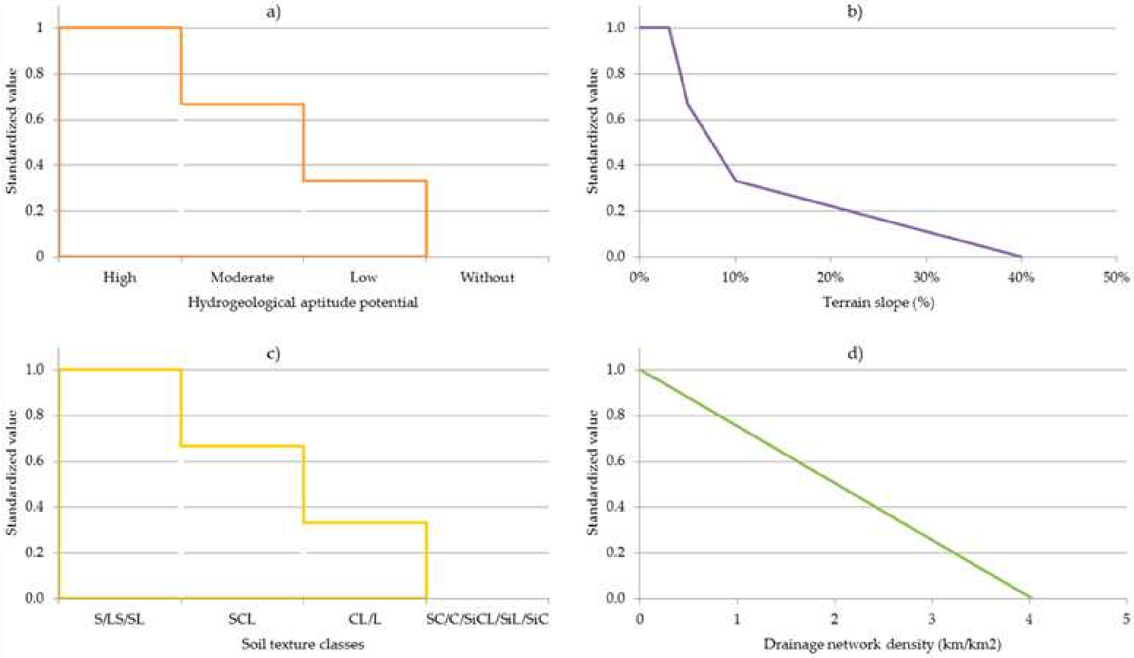
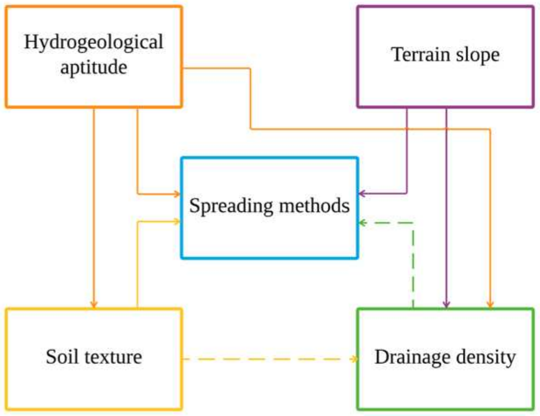


Figure 9: *Graphs showing how each of the parameters was standardized for (a) hydrogeological aptitude (top left), (b) terrain slope (top right), (c) soil texture (bottom left) and (d) drainage network density (bottom right). Source: (Bonilla Valverde et al., 2016, p. 11).*

2.2.2.2 Weighting

Furthermore, the influence on MAR suitability is not equal among the four parameters, and thus, they must be weighed based on a score. Hydrogeological aptitude for example highly influences suitability, since, in addition to its direct influence, hydrogeology has further effects on how soil texture is formed, and how drainage density turns out. By using this multi-influencing factor methodology, the interactions between the parameters were identified and the parameters weighted accordingly as shown in Figure 10.



Criterion	Score	Weight
Hydrogeological aptitude	1 + 1 + 1 = 3	43%
Terrain slope	1 + 1 = 2	29%
Soil texture	1 + 0.5 = 1.5	21%
Drainage density	0.5	7%
Total	7	100%

Figure 10: *Illustration on the weighting of parameters. The left graphic shows conceptually how parameters are weighted. Each arrow towards the center box (spreading methods) represents a score of 1 (full line) or 0.5 (dashed line). The right table shows the resulting scores of these lines and the weighting based on the relative score. Source: (Bonilla Valverde et al., 2016, p. 12).*

Hydrogeological aptitude is assigned a score of 3 due to its triple influence on MAR suitability (directly, via soil texture and via drainage density). Terrain slope influences suitability directly, as does drainage density; hence, a score of 2 is applied. Soil texture directly influences MAR suitability and has a minor effect on drainage density (score of 1.5), while drainage density itself only has a minor effect on MAR suitability (score 0.5).

By adding the standardized and weighted parameters, the suitability is calculated as a suitability range between 0.0, very low and 1.0, very high, with the following formula for each raster cell:

$$\mathrm{S} = (\mathrm{HA_s} * \mathrm{HA_w}) + (\mathrm{TS_s} * \mathrm{TS_w}) + (\mathrm{ST_s} * \mathrm{ST_w}) + (\mathrm{DD_s} * \mathrm{DD_w}) \tag{1}$$

Where:
S = Suitability
$\mathrm{HA_s}$ = Standardized raster value of the hydrogeological aptitude
$\mathrm{HA_w}$ = Weight of the hydrogeological aptitude
$\mathrm{TS_s}$ = Standardized raster value of the terrain slope
$\mathrm{TS_w}$ = Weight of the terrain slope
$\mathrm{ST_s}$ = Standardized raster value of the soil texture
$\mathrm{ST_w}$ = Weight of the soil texture
$\mathrm{DD_s}$ = Standardized raster value of the drainage density
$\mathrm{DD_w}$ = Weight of the drainage density

The results are shown in the next chapter.

2.3 Results

The calculation of MAR suitability results in a single map for the country showing the potential of the spreading methods, ranging from very high to very low suitability, as well as unsuitable areas previously excluded (see Figure 11 and Table 1). Roughly 30% of the country is suitable with either very high (12.4%) or high potential for MAR (18.0%).

It is noticeable that the MAR suitability decreases towards the south of the country, where areas are mainly of moderate or low potential. The largest coherent areas with (very) high MAR suitability are in the Northern and Tortuguero lowlands close to the Nicaraguan border and in the Northeast of Costa Rica. This is mainly due to the good hydrogeological conditions combined with gentle slopes. Here, areas can consist of several hundred square kilometers. In the South, mainly in the Southern Brunca region, areas with high potential are smaller than 100 km².

The same applies to the Northwestern region, where areas with high potential are scattered over large parts of the region. This is mainly due to the high variability of hydrogeological potential, slope, and soil types. However, even small areas are often several square kilometers in size, rendering them relevant for MAR considerations. Areas with medium to lower potential are usually concentrated around more suitable areas, forming a transition to less suitable MAR areas. This is mainly the case in the Northern half of the country, where the majority of moderately suitable areas are concentrated.

The opposite is true for (very) low potential areas. They are mainly found on the Pacific side in the Southern half of the country. This is largely influenced by the lack of hydrogeological potential due to the igneous rocks in the areas (gabbro, ocean floor rocks, mafic, and ultramafic igneous complexes). The regions with (very) low potentials are not as scattered as the areas with higher suitability and represent a large, connected area that stretches from the middle of the country to the border of Panama. Here, the large national parks Tapanti, Los Quetzales, Chirripo, and La Amistad combined with the (very) low areas make the search for suitable MAR sites difficult. However, even on the Peninsula, the Nicoya, some moderate and (very) high potential areas can be found, making it possible to consider MAR even in these areas, especially in river valleys.

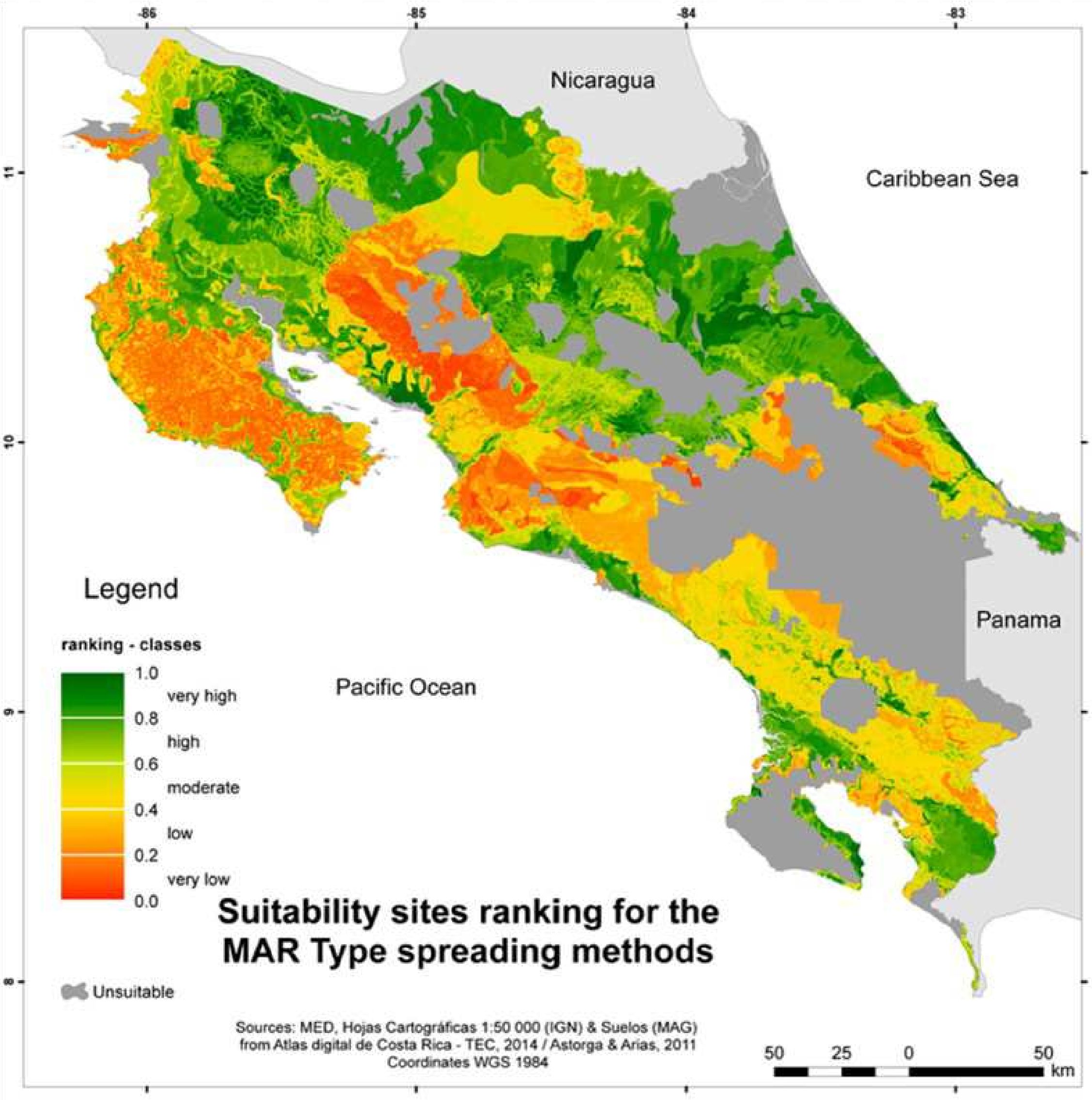


Figure 11: *Map showing the main result of the study as suitability map for MAR-type spreading methods in Costa Rica. It ranges from low suitability in red/orange to high suitability in green. Source: (Bonilla Valverde et al., 2016, p. 13).*

Table 1: *Areas with different suitability's as percentage of the total suitable area and the total area of the country of Costa Rica. An example is the following: 20.4% of the generally suitable areas are highly suitable for MAR type spreading methods which correspond to 12.4% of the country. Source: (Bonilla Valverde et al., 2016, p. 13).*

Class (GIS-MCDA Range)	***Percentage of Total Suitable Area***	***Percentage of Total Country Area***
Very high (1.0 – 0.8)	*20.4%*	*12.4%*
High (0.8 – 0.6)	*29.4%*	*18.0%*
Moderate (0.6 – 0.4)	*22.2%*	*13.5%*
Low (0.4 – 0.2)	*16.2%*	*9.9%*
Very low (0.2 – 0.0)	*11.8%*	*7.2%*

2.4 Discussion

The suitability map serves as a base map when starting the search for possible sites of MAR through spreading methods. It can serve also in the regional context or for single cities and communities to identify the general MAR suitability in the surrounding areas. This, however, is subject to certain limitations.

The availability of the hydrogeological aptitude and the soil texture as maps at a scale of 1:150,000 limits the information value of the results map at the smaller scale.

Whether a site is physically suitable for MAR depends on more conditions than the four main parameters that were used. Land cover, aquifer depth, storage capacity, lineaments, infiltration rate or geomorphology influence the suitability of MAR. Yet we limited our scope to the main parameters largely due to the unavailability of other data. Such conditions must be investigated further when considering MAR. This was partly considered in other studies (Patil & Mohite, 2014; Rahman et al., 2012; Ravi Shankar & Mohan, 2005; Saravi et al., 2006).

There is more to MAR than the physical condition of the underground. The availability of water and the water demand must be considered alongside the economic factors of storing and retrieving the water from the underground. Besides the drinking water sector, other water demands could influence the feasibility of investing in a MAR project. Examples are agricultural irrigation, water needs in the energy sector or the environmental aspects when looking at aquifer salinization, as well as wastewater availability for potential reuse. Considering the manifold objectives and possibilities of MAR, mentioned in Chapter 2.1.1, it becomes evident that MAR is an important technology in sustainable water management and that it should be included in a wider discussion on water use also in other sectors, such as the energy and food sectors. Remaining within the context of Costa Rica the following paragraphs will provide an overview of these sectors and discuss the possible role of MAR within the nexus of water, energy, and food.

The water use in Costa Rica is dominated by agriculture, which is responsible for 61% of total water withdrawal, followed by 32% for municipal and 7% for industrial use (FAO, 2022). While water stress in Costa Rica is low, with 5.9% of renewable water resources withdrawn, the agricultural sector's contribution to it is high (ibid.). As is common for agriculture, with 0.4 USD/m^3 its irrigated water-use efficiency is low compared to industrial (52 USD/m^3) and municipal use (43 USD/m^3) (ibid.).

The electricity mix of Costa Rica is dominated by hydropower. More than a dozen hydropower plants in the country produced 70.5% of the electricity demand in 2023, while 25.3% are generated by other renewables. Only 4.5% of the country's electricity is produced from fossil fuels i.e., oil (Ember, 2024).

To understand the role of MAR within this context, two examples of WEF-Nexus challenges within Costa Rica are discussed. The first example is the Lake Arenal project. Three hydropower dams built in the 1980s draw water from the Arenal Lake in the North of the country, providing already a quarter of the country's electricity demand (Echeverria, 2013). In addition to running through the three hydropower stations consecutively with an average of 100 m^3/s, the water is available to irrigate some 30,000 ha of land, which is more than 70% of Costa Rica's irrigated area as of 2013 (ibid.).

At Lake Arenal, the connection between water, agriculture, and energy becomes evident, and the issues accompanying it do too. Water demand by the agricultural and energy sectors is not the same. Hence, conflicts arise when and how much water shall be released, with the electricity company having the upper hand, controlling the upstream water flow through the dams according to electricity demand rather the irrigation needs (Echeverria, 2013). Water demand by agriculture is complex, with most needs in the dry season; however, with an increased demand by rice farmers in the wet season, when the electricity sector reduces flow to fill up the reservoir for the dry season. Some farmers even have specific hourly demands that the dam operators do not meet (ibid.). With a dominant position of the electricity utility, other stakeholders see little incentive to participate in coordination. Echeverria (2013) describes these and other conflicts and a high need for coordination and governance among all related stakeholders.

A second example is the planned Paacume Project that aims to improve food security in the Guanacaste Region, 100 km away from Lake Arenal, yet using its water. The project aims to invest in a new reservoir of 850 ha surface area, a hydroelectric dam transmission line of 55 km and distribution lines in an area of 17,000 ha (Servicio Nacional de Aguas Subterráneas, Riego y Avenamiento, 2020). With this infrastructure, the investors aim to provide an additional 1,730,000 m^3/d of water for electricity generation and, after that, 1,560,000 m^3/d for irrigation and 170,000 m^3/d for domestic drinking water use (ibid.). As the Paacume project is at the planning stage, there is no evidence of governance or coordination challenges. However, they may appear similarly during the implementation of such a grand project, including stakeholders from different sectors and with various interests.

The examples show the nexus of water, energy, and food in Costa Rica not only from a technical but also from a social and political perspective. Is MAR a technology that can provide solutions in such a setting?

The area of the Lake Arenal and the Paacume projects is in the Province of Guanacaste, which is dominated by high and very high suitability areas (see Figure 11). These promising underground conditions justify further investigations into locations where infiltration basins for MAR facilities could be located.

Some existing examples of MAR shall be compared with the situation in Costa Rica. Large-scale MAR applications using the spreading methods since the 1960s in agricultural areas in California and Arizona are presented in Scanlon et al. (2016). In the first example, a total of 710 ha of spreading basins provide an average infiltration rate of 27 mm/day (Scanlon et al., 2016). Even though this is a comparatively low infiltration rate, it would allow for a daily aquifer recharge of 190,000 m³. In the second example, eleven recharge basins with a total area of 130 ha recharge approximately 550,000 m³/day, equaling a recharge rate of 400 mm/day (ibid). Hydraulic conductivity rates vary from <10 mm/day in clay soils to >10 m/day in coarse sands (Bouwer, 1999 as cited in Bouwer, 2002). Even though the applicability of such MAR methods is unique for every site, depending on the hydrogeological and operational conditions, the suitability map and the examples indicate the following plausibility.

Assuming a conservative average infiltration rate of 50 mm/day, in spreading basins of 500 ha, a daily rate of 250,000 m³ could be infiltrated into the ground for later reuse via groundwater pumping. In the Lake Arenal areas, this would require 1.6% of the irrigated 30,000 ha to infiltrate 2.9% of the total water flow of 100 m³/s for flexible use by the farmers. In Paacume, 2.9% of the irrigated area could infiltrate 16.0% of the planned flow dedicated to irrigation.

Even though there is uncertainty regarding these examples, the suitability mapping and the estimations above show that a detailed analysis of MAR as a solution in such a context is warranted to allow farmers to use water more flexibly. In addition to the surface water flow from Lake Arenal, extra seasonal local water flows in the area, as well as treated wastewater, could additionally be included to reduce reliance on surface water from Lake Arenal.

Besides hydrogeological investigations further technical and economic studies are needed i.e., to investigate additional need and cost of electricity to recover infiltrated groundwater via pumping.

Scanlon et al. (2017) describe MAR as one solution in the WEF-Nexus. The above examples indicate the potential of MAR to contribute to a solution in the Lake Arenal and Paacume projects. However, a technical fix alone will not suffice due to the variety of challenges, such as the interlinkages between sectors and governance issues and conflicts, as described above. Further, legislation, power imbalances, governance in water allocation, coordination among stakeholders and several other topics must be understood and addressed. Implementing MAR alone cannot address this variety of topics.

An integrated approach, such as the WEF-Nexus, is needed to address major management questions at the interface of water, energy, and agriculture. Such a WEF-Nexus approach should enable the understanding of interlinkages between water, energy, and food and develop the sectors by including stakeholders in assessments and decision-making. This may lead to coherent infrastructure development and improved policy coherence to ensure long-term sustainability of these sectors.

This part looked at MAR suitability mapping and the combined challenges in the water, energy, and food sector at the example of Costa Rica. The topic is, however, a global one. MAR as a technology is implemented globally, as shown in Chapter 2.1.1. MAR suitability mapping can be applied in any region where respective data are available. The used datasets presented in Chapter 2.2.2 are not specific to Costa Rica and should be available in many regions. The wide application of the MAR suitability mapping (see Chapter 2.1.2) is an indication of this. Also, the described challenges in the water, energy, and food sector are not Costa Rica specific. Similar challenges can arise anywhere, where agricultural activity, water provision efforts, and electricity generation share the same resources.

During the time we carried out the research on MAR in 2015 and 2016, the concept of the WEF-Nexus rapidly increased in popularity within research and international development community (see Chapter 1, Figure 2 and Chapter 3.1.1.) with the aim to increase the efficiency among the water, energy, and food sectors by improving the governance across the sectors as well as reducing trade-offs and building synergies between them (Hoff, 2011). A WEF-Nexus Approach could thus tackle the challenges seen in the Lake Arenal and Paacume projects and many other contexts around the globe that are described e.g., in Hoff (2011). The understanding and evidence increased in the 2010s that the water sector cannot sustainably be managed without considering the interlinkages to the energy-, food-, and other sectors. This understanding sparked the conceptual debate on the WEF-Nexus described in Chapter 1. Aiming to contribute to this debate, we carried out different conceptual analyses on the Nexus between 2017 and 2020 that are described in Part B of this dissertation.

3 Part B – Conceptual Analyses

3.1 Introduction

What is known today as the WEF-Nexus has emerged in a chain of several key events and documents that we have described in Avellán & Roidt (2022). These initial events are shown in Figure 12. In summary, the Nexus can be dated back to the 1980s when the United Nations University (UNU) launched a Food-Energy Nexus Programme. The idea of a nexus between water, energy, and food was then debated and recognized in several global meetings and concepts, i.e., on virtual water or the notion of the perfect storm. It is, however, widely recognized that the background paper by Hoff (2011) to the Bonn 2011 Nexus Conference coined the idea of the Water-Energy-Food Nexus Approach. This idea then developed throughout the next decade. Other Nexus Approaches appeared as well, such as the Water-Soil-Waste Nexus (WSW Nexus) that has been developed at the UNU Institute for Integrated Management of Material Fluxes and of Resources (UNU-FLORES) since 2012 and regularly discussed at the Dresden Nexus Conferences.

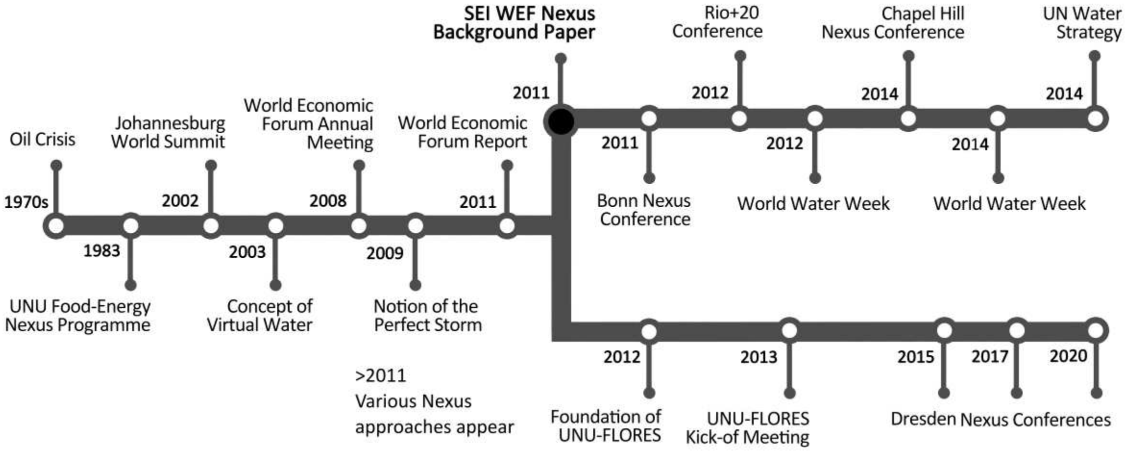


Figure 12: *Timeline of several international events that have discussed the idea of a nexus, culminating in the WEF Nexus Background Paper by Holger Hoff from the Stockholm Environment Institute in preparation for the Bonn 2011 Nexus Conference. After 2011, several events on the WEF-Nexus and the WSW-Nexus took place. Source: (Avellán & Roidt, 2022, p. 16).*

The term nexus stems from the Latin word "nectere" meaning "to bind" and refers to "connections", "causal links" or "a connected group or series" (Merriam-Webster, 2025c n.p.). Therefore, it can be stated that a nexus exists, e.g., between water and energy when describing the interlinkages between these sectors. Models that can represent such interlinkages may be described as nexus models, and policies that ensure an integrated development of these sectors may be called nexus policy. The term *Nexus Approach* often refers, however, to a specific concept like different integrated management approaches that have existed for some decades, e.g., Integrated Natural Resources Management (INRM), Integrated Water Resources Management (IWRM) or Integrated Solid Waste Management (ISWM) (see Chapter 3.3.1 for a description of the concepts). Questions on which sectors the Nexus Approach should entail, what it includes or doesn't include, which methods are being used, at which scale it must be studied or implemented, how it differs from other resource management approaches, and many other questions have been debated in the research community since 2011. Is the Nexus Approach a research paradigm, a policy tool, or a method that allows for integrated analysis of environmental parameters?

The expectations towards the Nexus are high. And if the Nexus Approach is to live up to these expectations such questions must be answered. The Nexus Approach must clearly be described conceptually. Contributions that aim to define and describe what the Nexus is, are considered *conceptual* in this dissertation. Conceptual contributions to the WSW-Nexus are provided in Roidt et al. (2017) and Avellán et al. (2017). This dissertation, however, focuses on conceptual contributions to the WEF-Nexus.

After its initial description, the WEF-Nexus was often set into the context of shortcomings of Integrated Management Approaches such as IWRM or INRM (Kurian, 2017; Lawford et al., 2013; Leck et al., 2015; Muller, 2015; Smajgl et al., 2016; Wichelns, 2017). A detailed analysis of this issue is provided in Avellán & Roidt (2022). Thus, when aiming to understand the concept of the Nexus, it provides useful insights into understanding integrated resources management approaches that existed before the Nexus became popular. The concepts of IWRM, INRM, and ISWM all claim to foster integration and to develop their respective sector in a sustainable manner (Roidt & Avellán, 2019). Thus, it will be useful to understand how these approaches are *defined*, what exactly is *integrated* and what the *features* of these approaches are to learn from these approaches when conceptualizing the Nexus. Before the results of this analysis are presented in Chapter 3.3, a look at the state of the art in such research is taken.

3.1.1 State of the Art in Conceptual WEF-Nexus Descriptions

The discussion on what the WEF-Nexus exactly is has not yet been conclusively clarified in scientific literature. As mentioned before, the most compelling evidence of this is that there is no commonly agreed-upon definition of the WEF-Nexus (see Chapter 3.3). Furthermore, there is no universally accepted standard textbook on a WEF-Nexus Framework. Articles asking questions such as "[w]hat are the elements included in the

FEW Nexus definition?" (Anandhi et al., 2023, p. 239), "How is nature defined in the Nexus? [and] [h]ow does the integration take place at a conceptual level?" (Lucca et al., 2025, p. 8) or how to govern and frame the Water-Energy-Food-Ecosystems (WEFE) Nexus (Mooren et al., 2025) are still recently published, further indicating that the debate is still ongoing.

In this ongoing process, several recent articles provide conceptual insights to the WEF-Nexus, e.g., by reviewing the nexus research of the past decade (Abdi et al., 2020; Albrecht et al., 2018; Apeh & Nwulu, 2024; Holmatov et al., 2023; Li et al., 2025; Purwanto et al., 2021; Rezaei Kalvani & Celico, 2024; Simpson & Jewitt, 2019a). Others provide bibliometric reviews by mainly showing how keywords, subjects, and trends have evolved (Chen et al., 2019; Fan et al., 2021; Lv et al., 2023; Opejin et al., 2020; Tayefeh et al., 2023; Zhu et al., 2020).

Furthermore, contributions on specific conceptual aspects of the Nexus Approach are being published such as Anandhi et al. (2023) contributing key ideas to how a Nexus definition can be derived that fits several contexts. Khan et al.(2022) provide the emerging themes and future directions of Nexus implementation and research. Sušnik & Staddon (2022) contribute new perspectives, challenges, and directions for future nexus research. Therefore, both contribute to further conceptually describing the WEF-Nexus.

Others provide various but specific contributions to a Nexus Approach, such as Higgins & Abou Najm (2020), who provide organizing principles and equations to model a WEF-Nexus, while Allouche (2024) looks at the WEF-Nexus by highlighting the tensions between its framing as a complex, interconnected system and as a political process shaped by power dynamics.

An overarching analysis of such conceptual contributions will form the state of the art of the WEF-Nexus. This is the aim of this part of the dissertation and presented in the results Chapter 3.3.

3.1.2 Research Deficit

Some articles investigate the shortcomings of Integrated Management Approaches. Biswas (2004) e.g., argues that in the past century, IWRM could not effectively manage water resources in an integrated way. The vague conceptual descriptions and hurdles in operationalization of IWRM and INRM have been lamented by Wichelns (2017).

A detailed analysis of Integrated Management Approaches and how they relate to the WEF-Nexus was, however, not available until our study in Roidt & Avellán (2019).

Only Wichelns (2017) addresses questions regarding the genesis and pertinence of the WEF-Nexus including reviewing the experiences of INRM and IWRM regarding integration and policy coherence. However, this article does not provide structured analysis of their goals, their features and what is to be integrated, to transfer this knowledge to conceptualizing the WEF-Nexus.

Furthermore, the above articles do not investigate the WEF-Nexus through this lens by proving conceptual clarity on where we stand with a definition of the WEF-Nexus, its features and the question on what exactly it is that shall be integrated.

3.1.3 Objectives

The detailed objectives of this chapter are to understand what we can learn from the conceptualizations of Integrated Management Approaches and how they may have shaped the concept of the Nexus. This objective is guided by the following questions:

- How are Integrated Management Approaches and the WEF-Nexus defined?
- What are the goals of the Integrated Management Approaches and the WEF-Nexus?
- What is to be integrated within the Integrated Management Approaches and the WEF-Nexus?
- What are the key features of the Integrated Management Approaches and the WEF-Nexus?

These detailed questions aim to answer the overall objective of this part as formulated in Chapter 1 (What constitutes the WEF-Nexus?).

3.2 Materials and Methods

The knowledge generated in this part is based on the literature review carried out in Roidt & Avellán (2019). It includes a systematic review of articles on the Integrated Management Approaches and the WSW-Nexus and the WEF-Nexus between 1990 – 2017 (first phase). Because this article was published in 2019 and the discussion on the WEF-Nexus is still ongoing, this dissertation provides an update of this research specifically for the WEF-Nexus. The same methodology is repeated for 2017 – 2025 (second phase), ensuring a consistent literature review methodology for the WEF-Nexus for the past three and a half decades.

A five-step review process is undertaken. This process involves identifying, selecting, appraising, collecting, and analyzing information (see Figure 13).

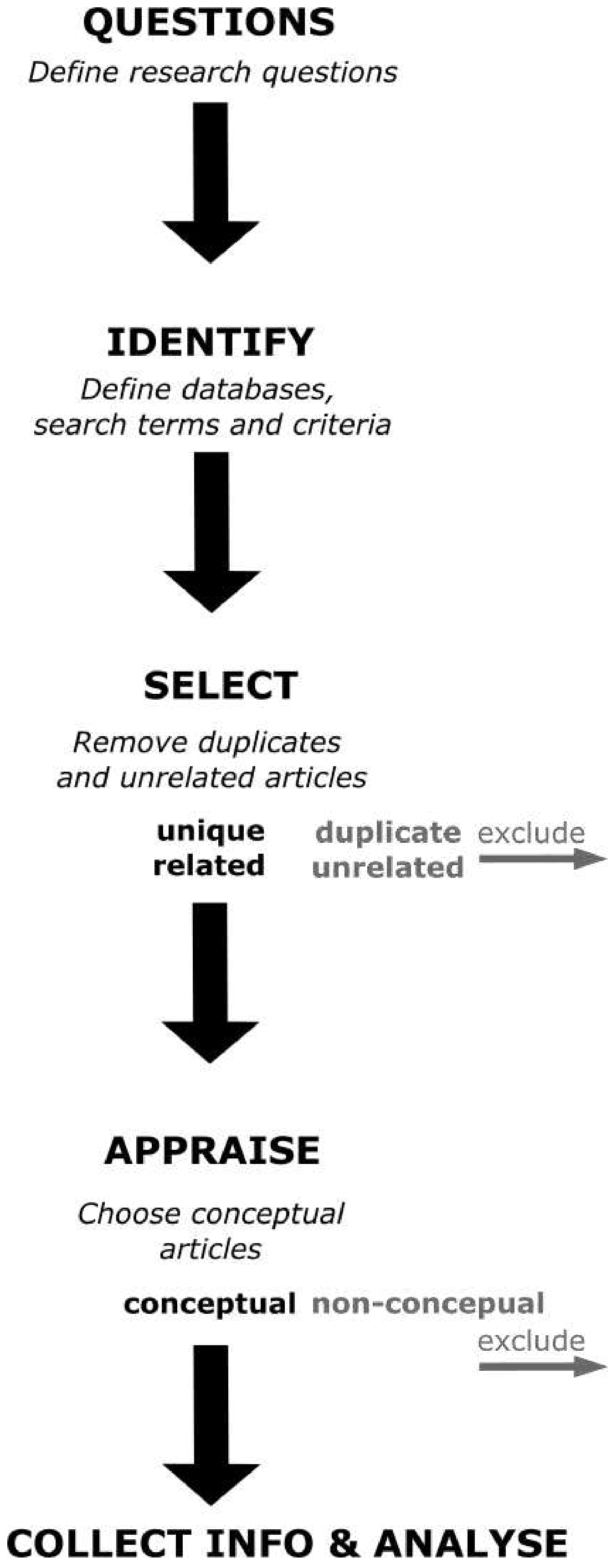


Figure 13: *Flow chart of the methodology to select relevant articles for analysis. A five-step review process is undertaken based on identifying, selecting, appraising, collecting, and analyzing information. Source: Adapted from Roidt & Avellán (2019, p. 611).*

In the identification step, the databases, search terms and criteria are clarified. The literature search was carried out on two major databases, Science Direct (Scopus) and Web of Science (previously Web of Knowledge), and included only peer-reviewed articles in English. For both phases, the exact same search term is used, i.e., searching for the full name of the Water-Energy-Food Nexus Approach or its abbreviation (e.g., WEF) in all combinations of the word. The terms are searched for in the title, abstract, and publication keywords (see Table 2).

During the selection step, duplicates from the databases are removed and excluded.

During the appraisal phase, the remaining articles are divided into two categories: conceptual and non-conceptual. This classification is done by reviewing titles and abstracts and is based on the author's conceptual judgment, as defined in Chapter 3.1. Conceptual articles discuss the Nexus Approach as a concept, addressing aspects such as its history, definition, goals, features, critiques, challenges, future research, frameworks, etc. Especially in the second phase of the search, this revealed several review articles.

In contrast, non-conceptual articles focus on specific aspects of the WEF-Nexus, such as a particular region (e.g., *A systematic analysis of Water-Energy-Food security nexus: A South Asian case study by* Putra et al. (2020)) or specific topics (e.g., *Integration of greenhouse gas control technologies within the energy, water and food nexus to enhance the environmental performance of food production systems* by Al-Ansari et al. (2017)). This category also includes methodological, empirical, and case study articles. Non-conceptual articles are excluded.

Table 2 provides the quantities of the literature research process, showing that out of 28 conceptual articles, the 14 most relevant articles were chosen. This is due to the methodology in Roidt & Avellán (2019), where the ten most cited articles were chosen for each approach. In addition, four relevant yet not highly cited articles – due to their recent publication at the time – were chosen for the WEF-Nexus. These 14 articles comprise the first research phase and the results of Roidt & Avellán (2019). In the second research phase, 59 conceptual articles were identified. All 59 articles were chosen for analysis to ensure insights from all conceptual articles, thus completing conceptual knowledge on the WEF-Nexus until August 2025. Such an increase in conceptual articles seems reasonable considering the increase in WEF-Nexus literature in recent years.

Table 2: *Relevant information and results of the literature research methods. It provides the exact search terms and times of research. It further gives an overview of the number of articles that were selected or excluded at different stages in the process. Finally, it presents the number of chosen articles and their citation number. Source: Expanded to research phase two from Roidt & Avellán (2019, p. 612).*

Databases and times of search	*Science Direct | Web of Knowledge | Times of search: April 2017 and August 2025*	
Search term	*((water AND food AND energy AND nexus OR water AND energy AND food AND nexus OR food AND energy AND water AND nexus OR food AND water AND energy AND nexus OR energy AND water AND food AND nexus OR energy AND food AND water AND nexus OR wef AND nexus OR few AND nexus OR wfe AND nexus OR few AND nexus OR ewf AND nexus OR efw AND nexus))*	
Search Criteria	*Years: Jan 1990 – Apr 2017 and May 2017 – Aug 2025 | English | Publications: Peer-Reviewed Articles | Search in: Title, Abstract, Keywords*	
	Phase 1	***Phase 2***
Total articles found	*180*	*4,370*
Duplicates	*42*	*1,972*
Unique articles	*138*	*2,398*
Non-conceptual articles	*110*	*2,339*
Conceptual articles	*28*	*59*
Number of chosen articles	*14*	*59*
Citation numbers	*[1 – 14]*	*[15 – 73]*

Due to the frequent citation of the 73 documents analyzed in the results chapter, the readability must be increased. Therefore, the analyzed documents on the WEF-Nexus are cited in square brackets, i.e., [1], while the corresponding source is given in Table 3. This citation style is only applied in Chapter 3.3.2 and only for the 73 analyzed documents. Other research that may be referenced in this chapter is cited as per the usual author-year style.

Table 3: *Citation number to the respective author-year citations to increase readability in Chapter 3.3.2. Source: own representation.*

No.	***Reference***	***No.***	***Reference***
[1]	*(Allan, 2003)*	*[38]*	*(Tayefeh et al., 2023)*
[2]	*(Lawford et al., 2013)*	*[39]*	*(Hejnowicz et al., 2022)*
[3]	*(Wong, 2014)*	*[40]*	*(Proctor et al., 2021)*

No.	Reference	No.	Reference
[4]	(Biggs et al., 2015)	[41]	(Higgins & Abou Najm, 2020)
[5]	(Endo et al., 2015)	[42]	(Tashtoush et al., 2019)
[6]	(Leck et al., 2015)	[43]	(Pahl-Wostl, 2019)
[7]	(Machell et al., 2015)	[44]	(Liu et al., 2017)
[8]	(Muller, 2015)	[45]	(Borge-Diez et al., 2022)
[9]	(Rasul & Sharma, 2016)	[46]	(Cai et al., 2018)
[10]	(Smajgl et al., 2016)	[47]	(Endo et al., 2018)
[11]	(Al-Saidi & Elagib, 2017)	[48]	(Endo et al., 2017)
[12]	(de Loe & Patterson, 2017)	[49]	(Johnson et al., 2019)
[13]	(Kurian, 2017)	[50]	(Lalawmpuii & Rai, 2023)
[14]	(Wichelns, 2017)	[51]	(McCarl et al., 2017)
[15]	(Holmatov et al., 2023)	[52]	(Molajou et al., 2023)
[16]	(Simpson & Jewitt, 2019b)	[53]	(Scanlon et al., 2017)
[17]	(Rezaei Kalvani & Celico, 2024)	[54]	(Taguta et al., 2022)
[18]	(Anandhi et al., 2023)	[55]	(Zarei et al., 2020)
[19]	(Allouche, 2024)	[56]	(Ali & Acquaye, 2024)
[20]	(Simpson & Jewitt, 2019a)	[57]	(Chen et al., 2019)
[21]	(Albrecht et al., 2018)	[58]	(de Andrade Guerra et al., 2021)
[22]	(Katz et al., 2020)	[59]	(Endo et al., 2020)
[23]	(Sušnik & Staddon, 2022)	[60]	(Fan et al., 2021)
[24]	(C. Zhang et al., 2018)	[61]	(Kurian et al., 2019)
[25]	(Abdi et al., 2020)	[62]	(Liebenguth, 2020)
[26]	(Khan et al., 2022)	[63]	(Orimoloye, 2022)
[27]	(Lazaro et al., 2022)	[64]	(Opejin et al., 2020)
[28]	(Purwanto et al., 2021)	[65]	(Wang et al., 2022)
[29]	(McGrane et al., 2019)	[66]	(Zhu et al., 2020)
[30]	(Li et al., 2025)	[67]	(Bigolin et al., 2025)
[31]	(Ojeda-Matos & Jones-Crank, 2025)	[68]	(Eriksson et al., 2025)
[32]	(Apeh & Nwulu, 2024)	[69]	(Karri et al., 2025)
[33]	(Farmandeh et al., 2024)	[70]	(Karri et al., 2025)
[34]	(Tariq & Willis, 2024)	[71]	(Mooren et al., 2025)
[35]	(Rhouma et al., 2024)	[72]	(Yupanqui et al., 2025)
[36]	(Lv et al., 2023)	[73]	(Lucca et al., 2025)
[37]	(Segovia-Hernández et al., 2023)		

3.3 Results

Chapter 3.3.1 first shows the outcomes of research on the Integrated Management Approaches, as carried out in the first research phase and presented in Roidt & Avellán (2019). Chapter 3.3.2 then presents the research on the WEF-Nexus, from the first research phase (ibid.) and the second research phase carried out during the preparation of this dissertation.

3.3.1 Integrated Management Approaches

Considering the objectives of this part, the following subchapters will look into the *definitions*, *goals*, *integration,* and the *features* of the Integrated Management Approaches and the WEF-Nexus.

3.3.1.1 Definition

The three Integrated Management Approaches are well defined and described in the analyzed documents.

IWRM: A systems approach to water management is Integrated Water Resources Management (IWRM) defined by the Global Water Partnership (GWP) as "a process which promotes the co-ordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems." (GWP, 2000, p. 22).

Throughout the years IWRM became a well acknowledged approach to water management until today (Crase et al., 2018; Jeffrey & Gearey, 2006; Petit, 2016). That it is still high on the global water managers agenda is shown through the commitment of SDG 6.5 specifically to IWRM with the goal to "implement integrated water resources management at all levels" (United Nations, 2015, p. 18).

INRM: The Consortium of International Agricultural Research Centers (CGIAR) defined a systems approach that shall improve the quantity and quality of natural resources related to agricultural activities called Integrated Natural Resources Management (INRM). INRM is "a conscious process of incorporating multiple aspects of natural resource use into a system of sustainable management to meet explicit production goals of farmers and other uses (e.g., profitability, risk reduction) as well as goals of the wider community (sustainability)" (CGIAR, 2000, p. 5).

ISWM: McDougall et al. (2001) defined Integrated Solid Waste Management (ISWM) in such a way that it incorporates economic, environmental, and social dimensions. The idea is that many options of waste management in collecting, transporting, treating, and disposing waste should not only be considered in simple comparisons, but also be carefully analyzed in accordance with an approach that can better economic and ecological efficiency through systemic and scientific approaches (Abounajm & Elfadel, 2004). The definition is that: "Integrated Waste Management (IWM) systems combine waste streams, waste collection, treatment and disposal methods, with the objective of achieving environmental benefits, economic optimization and societal acceptability. This will lead to a practical waste management system for a specific region" (McDougall et al., 2001, p. 15).

Table 4 gives an overview of different aspects of the Integrated Management Approaches, showing where they were derived from and what their boundaries, strengths, and weaknesses are.

Table 4: *Comparing overview of the three Integrated Management Approaches with regards to their systems, origin boundaries, strengths, and weaknesses. Source: (Avellán et al., 2017, p. 8).*

	ISWM	*INRM*	*IWRM*
Considered system	*Waste system*	*Agricultural system*	*Water system*
Derived from	*Municipal administration*	*Ecological and administrative boundaries*	*Hydrologic cycle*
Boundaries	*Municipality to intermunicipality*	*Farm to ecoregion*	*Catchment (any size) to river basin*
Strengths	*Clearly defined by municipal boundaries*	*Tangible focus on the farm level*	*Hydrologically useful*
Weaknesses	*Boundary definition is ambiguous when exceeding the municipality*	*Unclear or unpractical use of boundary considerations when exceeding the farm level*	*Altered hydrological usefulness through interbasin transfer (real and virtual water)*

In Avellán & Roidt (2022) and Avellán et al. (2017), we provide more in-depth analysis of the systems and boundaries of the Integrated Management Approaches and propose the system boundary for the WSW-Nexus. Due to the focus of this dissertation on the WEF-Nexus, this is not further elaborated. For further details, refer to Avellán et al. (2017).

3.3.1.2 Goals

The goals are presented in Table 5. The main difference between the three Integrated Management Approaches is that goals are sectors specific, yet it is the main common goal of all approaches to reach sustainability of the sector. Other shared goals by these approaches—particularly INRM and IWRM—are to consider and harmonize diverse, and sometimes conflicting, interests, and perspectives.

Table 5: *Overview of the goals of integrated management approaches. Source: Adapted from Roidt & Avellán (2019, p. 612).*

Approach	***Goals***	***Source***
INRM	*Enhance agricultural productivity in a sustainable manner* *Reconcile, consider, and synergize various (conflicting) interests* *Integrate the human and the natural system*	*(Dalsgaard & Oficial, 1997; Frost et al., 2006; Hagmann et al., 2002; Izac & Sanchez, 2001; Merrey et al., 2005; Twomlow et al., 2008; van Oosterzee et al., 2014)*
ISWM	*Combination of waste management options in a sustainable manner* *Maintenance or increase of public health and quality of life* *Protection of the environment* *Reduction, Reuse, Recycling/Recovery of waste* *Integration of waste materials, sources of waste, treatment methods, processes, technologies, sectors, and stages*	*(Abdoli et al., 2016; Clift et al., 2000; Huang et al., 2005; Levis et al., 2013; Marshall & Farahbakhsh, 2013; Memon, 2010; Menikpura et al., 2013; Solano et al., 2002; Wilson et al., 2012)*
IWRM	*Manage water, land and related resources in a sustainable manner* *Provide ecosystem solutions* *Balance various (conflicting) interests* *Integrate the human and the natural system*	*(Biswas, 2004, 2008; Grigg, 2008; Jønch-Clausen & Fugl, 2001; Jonker, 2002; McDonnell, 2008; Medema et al., 2008; Savenije & Van der Zaag, 2008)*

3.3.1.3 Integration

The question on integration is not as prominently featured as one might think for approaches with *integration* in its title. The analysis in Roidt & Avellán (2019) and (Roidt et al., 2017), however, showed different results for the three approaches as presented in Figure 14.

Even though the INRM literature does not explicitly mention what shall be integrated, we have concluded the following: It must be the system of land/soil that is to be integrated with related targets. In INRM literature, these are described as biodiversity, air, water, and nutrients.

For the waste sector, integration does not happen towards the outside but within the sector. Waste sources, types, treatment, and collection shall all be integrated with each other.

Only IWRM explicitly describes what must be integrated, reaching seven diverse aspects that need to be tackled, as shown in Figure 14.

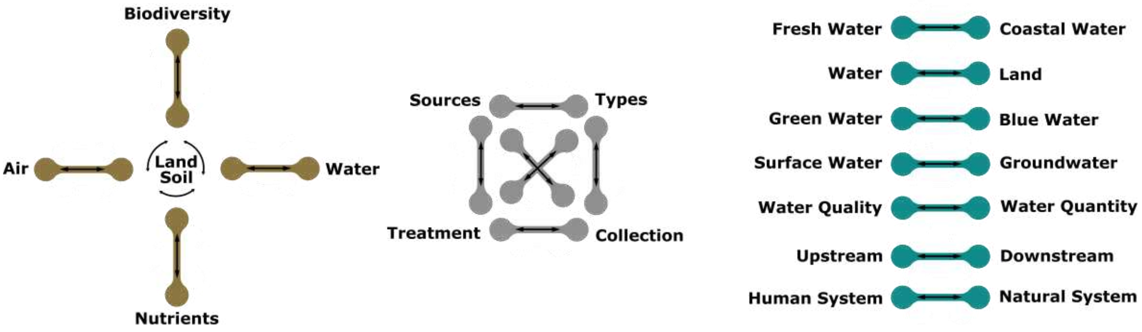


Figure 14: *Figure showing three graphical representations of what should be integrated into the Integrated Management Approaches of INRM (left), ISWM (center) and IWRM (right). In each approach, integration is described differently. Source: (Roidt & Avellán, 2019, p. 614).*

It cannot be definitively stated that integration is explicitly addressed within the Integrated Management Approaches. Although the wording appears similar, the three approaches show that the meaning of integration can vary considerably depending on context.

Furthermore, integration is rarely discussed at a conceptual level in the key documents of the approaches, and an exact definition of integration is not provided. Terms such as target systems, related targets, and integration receive surprisingly limited attention across the reviewed literature. One possible explanation is that these terms are part of a specialized jargon, presuming a shared, implicit understanding among readers.

Drawing on these insights, in Roidt & Avellán (2019), we introduce the idea to describe integration using the concept of *category of integration* along with the term *aspect*, which encompasses systems, subsystems, and comparable elements (see Figure 15).

Various aspects within an approach need to be connected. For instance, integration may involve linking systems (e.g., water-land), subsystems (e.g., surface water-groundwater), or other elements such as waste type and treatment, or upstream and downstream connections. This category of integration represents the linkage between two aspects within the integrated approach. Within one category, multiple interlinkages may exist that tie the two aspects together. Figure 15 illustrates this concept theoretically and through an example involving two aspects of IWRM.

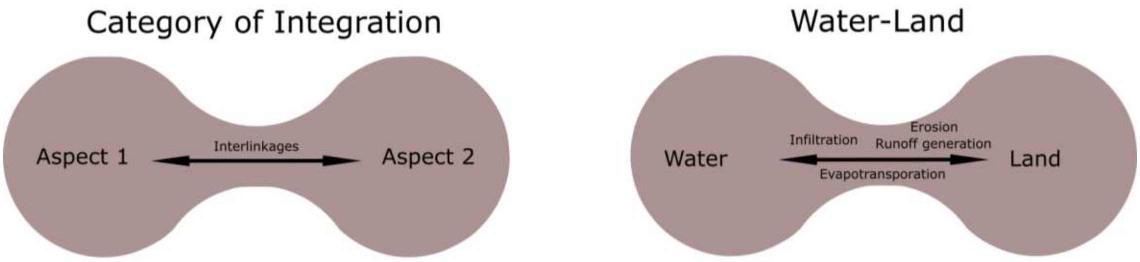


Figure 15: *Illustration showing a conceptual suggestion on how integration can be described. On the left, the concept is shown where two aspects are always integrated via one or more interlinkages. On the right, an example of how water and land are integrated via several interlinkages is given. Source: (Roidt & Avellán, 2019, p. 615).*

3.3.1.4 Features

A more detailed investigation leads to the features of the Integrated Management Approaches. More than 30 features are described in the analyzed literature. While some features are indeed specific to one approach, several features are shared by the approaches and have also been described as features in the WEF-Nexus. For easier comparison with the WEF-Nexus, the below described features are shown in Table 10 in Chapter 3.3.2.4.

The integrated approaches share a holistic, systems approach that embraces the complexity and uncertainty in the interlinked environment. Already, Integrated Management Approaches have transitioned away from reductionist, engineering-focused methods, adopting instead a broader approach to environmental resource management. As we described in Avellán et al. (2017), the concepts of reductionism and holism appear to be so familiar that none of the examined sources provides a deeper explanation of their precise definitions. Since they represent a crucial shared feature across all approaches, their meaning will be illustrated using the example of agriculture, drawing on Jordan (2013) in his discussion, *Holism vs. Reductionism in Environmental Science*. "Holism is looking at the properties of a system in its entirety, [...]. Reductionism is looking at mechanisms that influence these properties" (Jordan, 2013, p. 217). When analyzing system changes, reductionist science typically poses the question: "What is the mechanism that causes this effect?" (Jordan, 2013, p. 221). Consequently, reductionism seeks to uncover mechanisms or processes, often neglecting their role within the system's broader dynamics. In contrast, a holistic perspective connects various processes, offering the potential to optimize the performance of the overall system rather than focusing on isolated elements. Jordan (2013) supports this by stating that "[h]olism is necessary for solving management problems" (Jordan, 2013, p. 218). As presented in this article, holism adopts a broader vantage point to observe the complete system, acknowledging that this perspective is not fixed but depends on context: “A physiologist considers cell biology to be reductionistic. A cell biologist considers a molecular biology to be reductionistic”; conversely, the higher level is viewed as holistic (Jordan, 2013, p. 218).

Furthermore, the approaches mostly value participation and inclusion of stakeholders and to create knowledge in an interdisciplinary and transdisciplinary manner. These features were already part of the integrated approaches and have been taken up in the description of the Nexus Approaches as well. Other features, such as consideration of several scales, the reduction of trade-offs and the increase in synergies as well as focus on systems efficiency, combination of methods, tools, and modelling approaches are major features that are new in the Nexus and have not been described in previously defined Integrated Management Approaches.

These descriptions of the Nexus, described in Roidt & Avellán (2019) were published some years ago and thus the next chapter provides an update on how the Nexus has matured in the past decade with a focus on the WEF-Nexus.

3.3.2 The WEF-Nexus

3.3.2.1 Definition

A commonly agreed definition of the WEF-Nexus was not formulated yet ([17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [28], [31], [33], [39], [40], [41], [42], [43], [57], [58], [60], [63], [67], [69]). Several authors share the idea that formulation of one universal WEF-Nexus will not be possible ([15], [16], [17], [18], [19], [20], [21], [22], [23], [26], [39], [41], [43], [44], [69]) but that this is also not desirable due to the broad nature of the Nexus and its many manifestations ([18], [23]). Thus, a range of terms, categories, and definitions must be formed so that each party working with the Nexus can describe it in a tailored yet unambiguous way. In the last years several authors have contributed to this endeavor to help conceptualize and define a WEF-Nexus. This chapter does not present a definition of what is understood by the WEF-Nexus concept but aims to gather insights from literature that contribute to defining the WEF-Nexus in the future.

Zhang et al. ([24]) provide two different categories of a Nexus Approach, where category 1 refers to the “representation of interactions between different sectors aiming at grasping the overall characteristics of the complex system” (p. 5). Category 2 refers to “an analysis approach to quantify the links between nexus nodes” (p. 5). In a similar fashion, Allouche ([19]) argues that there are two traditions of the Nexus, where tradition 2 refers to “an analytical perspective to describe and better understand the interlinkages" (p. 506), which can therefore be seen equal to category 2 above. Tradition 2, in contrast to analysis, is a political one and revolves around "critical social science, with a focus on nexus power relations and the historical, cultural, and sociopolitical dimensions of these relationships" (p. 507).

Based on the above, three aspects can be part of a Nexus Approach. First *representation of interlinkages*, second *analysis of the interlinkages* and third *political consideration* of the Nexus.

More simple typologies to distinguish between Nexus Approaches are suggested by Zhang et al. ([24]). They differentiate whether a Nexus Approach represents two, three or four nodes of sectors or resources, i.e., Water-Electricity Nexus (2 nodes), Water-Energy-Food Nexus (3 nodes) or Water-Energy-Food-Ecosystems Nexus (4 nodes), and whether there is a center to the Nexus or not [24].

Jones-Crank [69] contributes towards defining the Nexus through two typology suggestions. The first is to clearly differentiate between multidisciplinarity, interdisciplinarity, and transdisciplinarity in a WEF-Nexus project, where she defines and discusses the terms in detail. The second is a differentiation between an equal consideration of the three sectors that she refers to as "balanced nexus" [69, p.5] or whether one sector is prioritized by putting more focus, e.g., in assessments. This is then referred to as the "sector-centric nexus" [69, p.5].

A comprehensive contribution to developing a definition was published by Anandhi et al. [18]. They provide a framework only to clear up the conceptualizations and definitions of a Nexus Approach. Their framework is based on several elements that describe a Nexus Approach. Five categories with several elements provide the possibility to create a Nexus definition that can range from complex to simple and broad to narrow, where each nexus stakeholder may describe a Nexus based on the provided elements tailored to what is exactly implemented.

Looking at the analyzed documents, it is not only evident that no common WEF-Nexus definition is in sight, but it also appears that there is no mutual understanding of what terminology to use when mentioning the different layers in which the WEF-Nexus can appear. Is the WEF-Nexus a research paradigm, an approach, a methodology or an instrument to achieve its goals? With one exception, none of these terms are defined in the analyzed documents.

This may be because terms such as *concept*, *approach*, *framework* or *paradigm* are commonly known, and their meaning is generally clear to the reader. However, when looking at the WEF-Nexus from a conceptual angle, we must reach clarity on defining some terms and layers.

To support the discussion on defining the Nexus, a conceptual clarity in the layers of the WEF-Nexus is proposed here by taking up the terms in the analyzed literature [15-73] and categorizing them (see Table 6). These layers are then later applied to the analyzed literature in Table 7.

The most abstract and general layer of the WEF-Nexus could be referred to as *Nexus Thinking*. This is done in 18 articles. Nexus Thinking can be seen as a general understanding that systems, processes, sectors or resources are intertwined and that they must be analyzed and managed in an interlinked way to contribute to nexus goals.

The term *Nexus Paradigm* is used in 13 articles. Within these documents, there is no clear tendency if the term is used in a generic way, as in Nexus Thinking, e.g., in [19], [30], [33], [43] or in a more specific way, where e.g., the WEF-Nexus is described as a paradigm ([39], [40]). A definition of paradigm is provided in Allouche [19] as „a universally recognizable scientific achievement that, for a time, provides model problems and solutions to a community of practitioners" (p. 503). It is based on the work of world-renowned philosopher of science Thomas Kuhn, who coined the term in his book *The Structure of Scientific Revolution*, dealing with paradigm shifts (Kuhn, 1970; Potthast, 2009). Adding to the above definition, a paradigm provides a framework in which new methods and theories are formulated. During a *paradigm shift,* a new paradigm replaces the existing one with new ideas and observations that the old paradigm could not explain. The relativity theory, which was not in line with Newtonian physics, is an example of such a paradigm shift (Potthast, 2009). Whether the Nexus is indeed a new paradigm, as claimed by Smajgl et al. (2016), or if it is part of the fashion to call new developments a paradigm shift as described by Potthast (2009), cannot be answered through this analysis. The analyzed literature, however, does not provide reason to speak of a Nexus Paradigm in Kuhn's sense. In the layered structure, it is therefore not used, and it is suggested that Nexus Thinking be spoken of as the uppermost category of the Nexus Approach.

The second layer could be referred to as the *Nexus Approach,* as done in 45 documents*, Nexus Concept* (in 36 documents) or *Nexus Framework* (in 30 documents). At this level, the Nexus is described conceptually. The question of *what* becomes relevant: *What* is integrated? *What* are the driving factors? *What* are other contextual influences? In many documents, the authors speak of approach, concept, and framework without a noteworthy difference. It must be assumed that the terms are used as synonyms since there is no evidence in the articles that there is a differentiation between the meanings of the three.

Table 6: *Suggested layers of the WEF-Nexus with the most used terms within each layer. Source: Own representation.*

Layers and Terms of the Nexus		
Layer	***Terms***	***Sources***
Layer 1	*Nexus Thinking*	*[18], [19], [20], [21], [23], [29], [30], [32], [36], [39], [41], [42], [43], [44], [46], [49], [66], [68].*
	Nexus Paradigm	*[19], [30], [33], [39], [40], [43], [46], [50], [52], [62], [68], [72], [73].*
Layer 2	*Approach*	*[15], [16], [17], [18], [19], [20], [21], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [37], [38], [39], [40], [42], [43], [44], [45], [46], [47], [50], [52], [54], [55], [56], [57], [58], [59], [61], [62], [63], [64], [68], [69, [70], [73].*
	Concept	*[15], [16], [17], [19], [20], [21], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37], [38], [39], [40], [41], [42], [43], [44], [48], [56], [57], [58], [59], [60], [67], [68], [73].*
	Framework	*[15], [16], [17], [18], [19], [20], [23], [24], [25], [27], [28], [29], [30], [34], [35], [36], [37], [38], [40], [41], [42], [44], [45], [46], [49], [50], [56], [61], [67], [70].*
Layer 3	*Methodology* *Method*	*[15], [16], [18], [19], [23], [24], [26], [27], [28], [30], [35], [36], [37], [38], [39], [40], [44], [45], [59], [60], [67], [72], [73].*
Layer 4	*Tool*	*[15], [16], [17], [18], [19], [21], [23], [24], [25], [27], [28], [29], [31], [32], [33], [34], [35], [36], [38], [39], [42], [45], [46], [47], [52], [53], [56], [57], [59], [62], [65], [66], [67], [68], [69], [71], [72], [73].*
Layer 5	*Case Study* *Project*	-

The Merriam-Webster dictionary provides the following definitions for the above terms.

- **Approach**: “the taking of preliminary steps toward a particular purpose” or “a particular manner of taking such steps” (Merriam-Webster, 2025a n.p.)
- **Concept**: “an abstract or generic idea generalized from particular instances” (Merriam-Webster, 2025b n.p.)
- **Framework**: “a basic conceptional structure (as of ideas)” (Merriam-Webster, 2025d n.p.)

All three definitions are in line with how the terms are understood in the analyzed literature.

Based on the given definition, the term “taking a nexus approach” appears to be more appropriate to the first general layer, where *Nexus Approach* refers to a general way of approaching the issues of interlinked systems, processes, sectors or resources. Some articles indeed use the term in such a generic way. However, most articles use the term *Approach* to refer to a specific Nexus Approach that includes already some conceptual guidance (i.e., the *WEF-Nexus Approach*). To avoid conceptual ambiguity, it is suggested that *Nexus Frameworks* is spoken of here. However, using the term Nexus Framework alone would not be sufficient since it must be specified which Nexus Framework one refers to, i.e., a *WEF-Nexus Framework* or a *WSW-Nexus Framework*. A WEF-Nexus Framework, however, does not yet describe detailed steps towards the goal.

This is done in the third layer of the Nexus, described as *Nexus Methodology* (or Method), a term used by many authors. Most of the time, the term is used when describing more concrete steps within a WEF-Nexus Framework. However, sometimes the term method is used when describing a WEF-Nexus Framework itself ([17], [32], [42]). Some others use it as an overarching term for nexus frameworks or modelling systems ([29]) or refer to Nexus Methods as what is considered here as a Nexus Tool ([21, 30]).

Here, *Nexus Methodology* is defined as a described structure of how analysis, decision making and policy advice is generated. Methodologies must contain information on the scale, the interlinkages, whether quantitative analysis or qualitative description is used and many more details. Whenever a Nexus Methodology is described, it must be able to be implemented. If this is not the case, it is rather a framework but not a methodology.

Whenever a Nexus Methodology is carried out, supporting tools are used to analyze the interlinkages, support decision making, facilitate stakeholder participation, etc. The term *tool* is used by most authors. Only six documents do not use the term tool in this sense ([20], [22], [26], [30], [41], [43]), and a few authors also refer to the WEF-Nexus as a tool ([26], [37], [40], [44], [50], [63]).

Here, the term *Nexus Tool* is understood as a set of techniques that are used to achieve the outcomes defined in the Nexus Methodology. This includes a wide range, from e.g., stakeholder engagement tools to mathematical models. Some examples that are mentioned in the documents are decision support tools [16], [18], [19], [39], [44], [62], [64] mathematical integrated models [18], [19], [21], [29], [56] footprinting [29], LCA

[18], [29], [37], [40], [59] visualization tools [18], [29], simulation [24], [38] or nexus metrics [31], [34], [35], [40].

A structured overview is given in [21] and [53] with more than 40 Nexus Tools in each article. The authors, however, refer to them as nexus methodologies, while according to the description above they could be recognized as tools.

The fifth layer in the Nexus is the real-world application in a case study or implemented project, adapted or new policies etc. Here the examples are so numerous that further categorization is not intended.

The above-described nexus layers follow a hierarchy. Nexus Thinking is the most abstract at the top, while Nexus Projects are at the bottom as the most concrete means to achieve nexus goals.

Looking from the bottom towards the top, each lower layer must be part of a defined category of the upper layer. A Tool that doesn't belong to a Nexus Methodology and a Nexus Framework is not a Nexus Tool. This logic can be applied to Roidt & de Strasser (2018). The different Nexus Tools MuSIASEM, OnSSET, WEAP-LEAP etc. are part of the six step Nexus Assessment Methodology which belongs to the Water-Energy-Food-Ecosystems Nexus Framework, which is part of general Nexus Thinking.

Looking from the top layer, it is different. A Nexus doesn't have to go all the way from the top to the bottom. A Nexus can be described as a framework without a methodology and respective tools, which is the case in several descriptions. The Water-Energy-Food-Forest Nexus is e.g., conceptually defined as a framework; however, it does not have a methodology or tools to implement it.

This categorization is applied to extract descriptions of different Nexus examples mentioned in the analyzed literature. This revealed 32 different Nexus Frameworks. Table 7 shows these Nexus Frameworks including their categorization into the four layers, starting with the descriptions that mainly shaped Nexus Thinking in rows A and B.

WEF-Nexus Thinking was mainly shaped by three authors. The descriptions of a global nexus mainly between water, energy, and food are analyzed in Hoff (2011), World Economic Forum (2011b) and Beddingtons (2009) description of the perfect storm. While the World Economic Forum (2011b) and Beddington (2009) stay with an analysis of the situation, Hoff (2011) goes further. He describes somewhat of a framework to the WEF-Nexus, including the features of aiming to reduce trade-offs and increase synergies. The three authors shaped what can be referred to as Nexus Thinking but did not provide any methodologies or tools. After 2011, however, several Nexus Frameworks appeared that are influenced by Nexus Thinking and mostly refer to the above as the rise of Nexus.

Between 2012 and 2022, several new Nexus Frameworks were described, where some consider additional sectors to the WEF-Nexus, i.e., land, climate, ecosystems or specifically forests, while others provide Nexus Frameworks on a resources basis, i.e., the Resource Nexus (Andrews-Speed et al., 2012) or the WSW-Nexus (R. Lal, 2015). More complex frameworks are provided, i.e., a WEF-Nexus considering Policies, Institutions, and Knowledge (WEF-PIK) (Stringer et al., 2018) or a polycentric governance analysis of the WEF-Nexus (Srigiri & Dombrowsky, 2022).

Some remain a Nexus Framework without further guidance on a methodology, while others provide a new framework, a methodology and respective tools for analysis. On the contrary, several articles provide tools for nexus analysis without providing a new Nexus framework, but just a general reference to the WEF or WEFE Nexus Frameworks (see Table 7).

Table 7: *All Nexus Frameworks mentioned in the analyzed documents. The left column shows the number of the framework in alphabetical order to avoid mixing with citation numbers. The letters AA – AG are a continuation of the numbering after the letter Z. Each framework is categorized in the above-developed layers. The column "Author/Year" is the source of the main authors of the mentioned nexus framework, while the column "source" shows the analyzed documents in which the approach was mentioned. Source: Own representation.*

Nr	***Name***	***Nexus Thinking** -> **Framework** -> **Method** -> **Tool***	***Author/Year***	***Source***
A	*Water-Energy-Food Security Nexus*	*Nexus Thinking: In hindsight, the background paper shaped the Nexus Paradigm.* *Framework: There is a need for an approach that reduces trade-offs and builds synergies across sectors.* *Methodology: -* *Tools: -*	*(Hoff, 2011)*	*[15], [16], [17], [19], [20], [21], [22], [24], [27], [28], [29], [30], [32], [35], [36], [37], [39], [40], [42], [43], [44], [46], [47], [48], [50], [52], [54], [55], [57], [58], [59], [60], [62], [63], [64], [66], [67], [68], [69], [72]*

Nr	***Name***	***Nexus Thinking** -> **Framework** -> **Method** -> **Tool***	***Author/Year***	***Source***
B	*Water-Food-Energy (Climate) Nexus*	*Nexus Thinking: Warning that strategies must focus on the Water-Energy-Food Nexus and climate interlinkages.* *Framework: -* *Methodology: -* *Tools: -*	*(World Economic Forum, 2011a, 2011b)*	*[16], [17], [19], [20], [21], [22], [24], [25], [27], [28], [29], [30], [32], [35], [36], [39], [41], [42], [43], [44], [50], [54], [55], [57], [58], [60], [63], [64], [66], [67], [68], [72]*
C	*The Resource Nexus*	*Framework: Description of a resource Nexus between land, water, energy, food, and minerals.* *Methodology: -* *Tools: -*	*(Andrews-Speed et al., 2012)*	*[28], [29]*
D	*Water-Energy-Land Nexus*	*Framework: A Nexus considering water, energy, and land (for forests, biodiversity, agriculture, human infrastructure and settlements).* *Methodology: -* *Tools: -*	*(European Commission, 2012)*	*[28], [29]*
E	*Climate change-land-use-energy-water strategies (CLEWS)*	*Framework: The idea is that climate, land-use, energy, and water strategies should be analyzed in an integrated framework.* *Methodology: No new analysis tool development, but process how data is exchanged between models.* *Tools: Sectoral models (LEAP, WEAP, AEZ)*	*(Howells et al., 2013)*	*[16], [28], [29], [37], [41], [42], [69]*

Nr	**Name**	**Nexus Thinking -> Framework -> Method -> Tool**	**Author/Year**	**Source**
F	*Water-Energy-Food Security Nexus for landscape investment and risk management*	*Framework: WEF-Nexus security approach with focus on implementation and ecosystem goods and services, as well as research, policy, and investment.* *Methodology: A Basic four-step participatory planning process.* *Tools: -*	*(Bizikova et al., 2013)*	*[16], [17], [24], [28], [29], [41], [47], [48]*
G	*Multi-Scale Integrated Assessment of Society and Ecosystem Metabolism (MuSIASEM)*	*Framework: General reference to the WEF-Nexus.* *Methodology: General reference to the WEF-Nexus.* *Tools: Analyze the metabolic patterns of energy, food, and water in relation to socioeconomic and ecological variables with MuSIASEM (Multi-Scale Integrated Assessment of Society and Ecosystem Metabolism)*	*(Giampietro, 2013)*	*[29], [48]*
H	*Nexus Webs*	*Framework: General reference to the WEF-Nexus* *Methodology: Nexus Webs will analyze linkages between water use and human livelihood.* *Tools:-*	*(Overton et al., 2013)*	*[29]*
I	*Water-Energy-Food/Feed/Fibre/Fuel and climate change Nexus*	*Framework: Nexus to understand the global linkages between water, energy, food/feed/fiber/fuel and climate change.* *Methodology: -* *Tools: -*	*(WBCSD, 2014)*	*[29]*
J	*FAO Water-Energy-Food Framework*	*Framework: FAO WEF-Nexus Aproach, including sectors, resources, goals/Interests, stakeholders, and drivers of a Nexus.* *Methodology: Three-step WEF-Nexus assessment.* *Tools:* *- Tools for stakeholder dialogue.* *- Quantification with several indicators and a Radar Diagram.*	*(FAO, 2014; Walking the Nexus Talk, 2014)*	*[17], [28], [29], [44], [41]*

Nr	**Name**	**Nexus Thinking** -> **Framework** -> **Method** -> **Tool**	**Author/Year**	**Source**
K	*WEF-Nexus livelihood framework*	*Framework: General reference to the WEF-Nexus* *Methodology: Conceptual framework to monitor environmental livelihood security (ELS) of WEF systems.* *Tools: -*	*(Biggs et al., 2015)*	*[40]*
L	*Water-Energy-Food Nexus at Texas A&M*	*Framework: Refers to a general WEF-Nexus.* *Methodology: Framework to quantify flows between water, energy, and food systems.* *Tools: WEF-Nexus Tool 2.0*	*(Daher & Mohtar, 2015)*	*[17], [29], [40], [72]*
M	*Water-Soil-Waste Nexus*	*Framework: View on resource flows in the Nexus, especially water, soil, and waste.* *Methodology: -* *Tools: -*	*(R. Lal, 2015)*	*[48], [66]*
N	*Water-Food-Energy Nexus*	*Framework: Sectorally balanced Nexus between water, food, and energy.* *Methodology: -* *Tools: -*	*(Smajgl et al., 2016)*	*[24], [29]*
O	*Transboundary Water-Energy-Food-Ecosystems Nexus*	*Framework: Taking into account the links and dynamics between water, energy, food, and ecosystems to enhance resource efficiency and good governance in transboundary river basins.* *Methodology: Nexus Assessment of a transboundary basin as a six-step process.* *Tools: Different analytical tools (MuSIASEM, CLEWS Models (see CLEWS), OnSSET, WEAP-LEAP, WHAT-IF, e-nexus, WEF-Nexus Tool, DAFNE)*	*(de Strasser et al., 2016; Roidt & de Strasser, 2018)*	*[16], [28], [29], [71]*
P	*Water-Energy-Food Nexus and Water Footprint Framework*	*Framework: Refers to a general WEF-Nexus.* *Methodology: Representation of WEF-Nexus sectors in relation to water footprint accounting.* *Tools: -*	*(Vanham et al., 2019)*	*[17]*

Nr	Name	Nexus Thinking -> Framework -> Method -> Tool	Author/Year	Source
Q	*Land-Water-Energy Nexus*	*Framework: Description of a Nexus between land, water, and energy, including megatrends as context and policy objectives of the Nexus.* *Methodology: A multi-model framework to quantify bottlenecks in the Nexus based on biophysical system analysis and economic analysis.* *Tools: (1) Biophysical analysis (IMAGE), (2) Economic Analysis (ENV-Linkages)*	*(OECD, 2017)*	*[28]*
R	*WEF-PIK Resilience Framework*	*Framework: Combining the interconnection of water, energy, food (WEF) with policies, institutions, and knowledge (PIK) in the context of resilience.* *Methodology: -* *Tools: -*	*(Stringer et al., 2018)*	*[17], [39]*
S	*Ecosystem-Water-Food-Land-Energy Nexus and Life Cycle Assessment.*	*Framework: Nexus Matrix for food security, placing ecosystems at the centre of a water, food, energy, land Nexus. Combination of Nexus Matrix with LCA.* *Methodology: -* *Tools: -*	*(Karabulut et al., 2018)*	*[41]*
T	*WEF-Nexus Framework in South Africa*	*Framework: General reference to the WEF-Nexus.* *Methodology: WEF-Nexus Analytical Livelihoods Framework (ALF) will monitor the performance of resource development in southern Africa and WEF sustainability indicators.* *Tools: -*	*(Mabhaudhi et al., 2019)*	*[31]*
U	*Water-Energy-Land-Food-Climate Nexus for Resource Efficiency (SIM4NEXUS)*	*Framework: Investigation of interlinkages between water, energy, food, land, and climate systems with the aim to create synergies and reduce trade-offs, motivated by a sustainable and integrated management of resources. (Ramos 2022)* *Methodology: A six-step methodology to reach outcomes.* *Tools: (1) Serious Game, (2) Different System Dynamics Models (SDM) (E3ME-FTT, MAGNET, CAPRI, IMAGE-GLOBIO, OSeMOSYS, SWIM, MAgPIE-LPJmL)*	*(Ramos et al., 2022)*	*[17],[29], [28]*

Nr	**Name**	**Nexus Thinking** -> **Framework** -> **Method** -> **Tool**	**Author/Year**	**Source**
V	*Organizing Principle for the Water-Energy-Food Nexus*	*Framework: Refers to a general WEF-Nexus.* *Methodology: Organizing roadmap for conceptual and mathematical representation of the WEF-Nexus including sectors, modifying factors, system connections incl. equations to describe the Nexus.* *Tools: -*	*(Higgins & Abou Najm, 2020)*	*[16]*
W	*Policy Coordination across the WEF*	*Framework: General reference to the WEF-Nexus.* *Methodology: Generic description of four steps to improve policy coordination between WEF sectors.* *Tools: -*	*(Rasul & Neupane, 2021)*	*[31]*
X	*Water-Energy-Food-Health Nexus*	*Framework: Argues to put health at the heart of the WEF-Nexus.* *Methodology: -* *Tools: -*	*(Nuwayhid & Mohtar, 2022)*	*[30], [72]*
Y	*Water-Energy-Food-Forest Security Nexus*	*Framework: Forest security to form a fourth foundational dimension of the WEF-Nexus (Melo et al., 2021).* *Methodology: -* *Tools: -*	*(Melo et al., 2020)*	*[29], [16], [30]*
Z	*FEW-WISE Nexus*	*Framework: Integrate food, energy, water, well-being and resilience to evaluate and predict the dynamic in the system.* *Methodology: A five-step process for qualitative and quantitative assessment.* *Tools: (1) System Dynamics Modeling (SDM), (2) Development of indices.*	*(Yadav et al., 2021)*	*[30]*

Nr	**Name**	***Nexus Thinking*** **->** ***Framework*** **->** ***Method*** **->** ***Tool***	**Author/Year**	**Source**
AA	*Water-Energy-Food-Ecosystems Modelling Toolkit*	*Framework: Refers to a general WEFE Nexus.* *Methodology: -* *Tools: Structure of different models that combine socio-economic and biophysical aspects in the Water Energy Food Ecosystems Nexus.* *Irrigation Simulation (WaSIm, Energy Balance), Environmental assessment (Open LCA), Socioeconomic Analysis (Partial Equilibrium Model).*	*(Correa-Cano et al., 2022)*	*[16]*
AB	*Sustainable WEF-Nexus to integrate models for social, economic, policy, and institutional developments*	*Framework: General reference to the WEF-Nexus.* *Methodology: Integration of socio-anthropological models with bio-physical models under WEF-Nexus.* *Tools: A Decision support tool called DAF.*	*(Akinsete et al., 2022)*	*[31]*
AC	*Analytical Framework of WEF Security*	*Framework: General reference to the WEF-Nexus.* *Methodology: Three-phase analysis to calculate WEF-Nexus security using the TOPSIS technique.* *Tools: -*	*(Hao et al., 2022)*	*[31], [39]*
AD	*Polycentric Governance Analysis of the WEF-Nexus*	*Framework: General reference to the WEF-Nexus.* *Methodology: Framework for WEF-Nexus governance based on the Institutional Analysis and Development (IAD) framework and the concept of Networks of Adjacent Action Situations (NAAS).* *Tools: -*	*(Srigiri & Dombrowsky, 2022)*	*[39]*

Nr	**Name**	***Nexus Thinking*** *->* ***Framework*** *->* ***Method*** *->* ***Tool***	***Author/Year***	***Source***
AE	*WEFE Nexus Governance Approach*	*Framework: General reference to the WEF(E) Nexus.* *Methodology: 1) Problem identification, 2) stakeholder dialogue on WEFE goals and policies, 3) Governance mechanisms through realizing WEFE goals and polices, 4) Implementation.* *Tools: NXGAT, Casual Loop Diagrams (CLD), Conceptual Maps (CM), System Dynamic Modelling (SDM).*	*(Mooren et al., 2025)*	*[71]*
AF	*Water-Energy-Land-Food Nexus (WELF)*	*Framework: A conceptual framework that puts land at the center of the Nexus, that considers direct and indirect drivers and aims at human well-being and environmental sustainability.* *Methodology: -* *Tools: -*	*(Ringler et al., 2013)*	*[24], [57], [72]*
AG	*Hybrid WEF-ecosystems Nexus*	*Framework: Reference to WEF-Nexus and WEFE Nexus, considering – in addition – social-ecological systems (SES) and the interlinkages between the WEF-Nexus and SES.* *Methodology: -* *Tools: -*	*(Lucca et al., 2025)*	*[73]*

3.3.2.2 Goals

The goals of the WEF-Nexus, as analyzed in Roidt & Avellán (2019), are presented in Table 8

Table 8: *Overview of the goals of the WEF-Nexus. Source: Adapted from Roidt & Avellán (2019, p. 612).*

Approach	***Goals***	***Source***
WEF-Nexus	*Achieve water-, energy- and food security* *Support Sustainable Development and the SDGs* *Increase resource efficiency and optimization* *Inform resource governance and promote rational decision-making* *Enhance policy coherence and cooperation within and between sectors* *Shift from integration within the sector to cross-sectoral integration*	*[2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [14]*

In comparison with the goals of Integrated Management Approaches (see Table 5), it becomes clear that achieving sustainability is a goal that all approaches share. In the WEF-Nexus, this is specifically connected to the SDGs. The WEF-Nexus's goal is to consider and synergize different views and interests, which is something that it has in common with INRM and IWRM. New in the WEF-Nexus is striving to inform resource governance, promote rational decision making as well as policy coherence and the shift towards cross-sectoral integration.

These initial goals haven´t changed. The analyzed documents of the second research phase don´t show any indication that the goals of the WEF-Nexus are different today. Hence, they remain as relevant and up to date as they were a decade ago.

3.3.2.3 Integration

By applying the *category of integration* (see Chapter 3.3.1.3) we concluded in Roidt & Avellán (2019) based on the first research phase, that it is the aspect of water, energy, and food that are to be integrated via the interlinkages between them in both directions.

Also, in the second research phase it is ambiguous what is understood by integration. Only Hejnowicz et al. [39] touch upon the topic of integration briefly by citing Al-Saidi and Elagib (2017) who question on whether integration refers to *incorporation* of the sectors, or *cross-linking* the sectors with highlighted priorities or *assimilation* in which strategies are applied from one sector to another. Other than that, the analyzed documents do not address the question of integration further.

There is however common agreement – also in the second research phase – that it is water, energy, and food that are to be integrated under the WEF-Nexus, while most sources speak of the water, energy, and food sectors ([15], [16], [18], [19], [20], [21], [24], [27], [28], [36], [37], [38], [42], [44], [46], [50], [52], [54], [57], [59], [60], [62], [63], [64], [65]), some of systems ([22], [26], [47], [52], [58], [67], [69], [70]) or just water, energy, and food ([17], [29], [30], [32], [62]). Several authors refer to water, energy, and food resources ([17], [18], [21], [25], [28], [30], [37], [41], [48], [49], [52], [54], [55], [57], [58], [59], [63], [66], [72]). Generally, the terms are not further explained or defined, which is also confirmed in [68]. The cited sources above also show that several authors use several terms in the same context.

Integration between water, energy, and food is referred to as six different *resource interactions* by Li et al. [30]. They investigated how many such resource interactions are studied in over 800 nexus studies. When studies are theoretical, almost half of the studies tackle all six interactions, while for empirical research, only 4% investigate all six interactions in the WEF-Nexus. Most empirical studies investigate two, three or four interactions [30]. Which specific interlinkages within these resource interactions are tackled is not presented in [30] and is not discussed in any of the analyzed documents. Given the complexity of the WEF-Nexus, identifying every possible interlinkage, only from a natural science perspective, could range in the thousands, from groundwater infiltration at the farm scale to virtual water of coal at the global scale, tackling different land uses, energy production resources, etc. The focus should therefore be on the *relevant* interlinkages – a recommendation we have formulated for the WSW-Nexus as well in Roidt et al. (2017). Hence, when tailoring the WEF-Nexus to a scale, location, etc., it should be one key part of identifying which interlinkages are relevant for that one specific case.

There is more to integration in the WEF-Nexus than just water, energy, and food as shown in Table 9 and described below.

Mainly climate (change), land(use) and ecosystems are mentioned to be interlinked with the WEF-Nexus either through existing frameworks that include the category e.g., a Water-Energy-Food-Ecosystems Nexus or through discussion in the analyzed literature.

Climate change is mentioned – at least on a general level – in a majority of WEF publications ([15]) and has trended in the literature throughout the past decade ([27], [35]). Some sources argue to consider climate (change) in a WEF-Nexus ([17], [20], [23], [27], [30], [38], [50], [58]) or say that we must understand how climate resilience in the Nexus can be enhanced ([39], [38]). Others say that climate change is an important challenge ([36], [37]), variable ([25]), external factor ([15], [24], [58]) or driver of the

WEF-Nexus ([42]). [48] identified several climate-related nexus projects. [50] and [70] refer to the WEF-Nexus as an instrument to address climate change. [72] developed a WEF-Nexus Security Index that includes, among water, energy, food, disaster risk and climate change. Different bibliometric analyses describe climate (change) as one of the top keywords or trends ([57], [60], [65]), and one of them claims that climate change is a new element associated with the WEF-Nexus ([60]). Four nexus frameworks in Table 7 explicitly consider the interlinkages with climate or the emissions from the WEF-Nexus sectors.

To consider ecosystems in the WEF-Nexus is argued or described by several authors ([20], [23], [25], [26], [30], [43], [49], [55], [57], [67]). [50] points to the WEF-Nexus as a tool to combat environmental degradation. Reviews show that ecosystems are a key topic in WEF-Nexus research ([35]) and that it was debated throughout the past ten years ([27], [30], [72]). Research with the ecosystem's perspective on the Nexus is rapidly growing ([40]), and [60] claims that ecosystems are a new element associated with the WEF-Nexus. [68] recommend to integrate ecosystems into nexus research and [71] put forward a WEFE Nexus Governance Approach that puts ecosystems at the center, challenging the anthropocentric perspective of other WEF-Nexus Approaches. Different bibliometric analyses describe environment, ecosystems or ecosystem services as one of the top keywords or trends ([60], [64], [66]). The most comprehensive conceptual analysis is provided by [73], who provide a concept on how nature can be integrated with the WEF-Nexus through a hybrid approach that harmonizes the WEF-Nexus, the component of ecosystems and the concept of social-ecological systems. Six frameworks in Table 7 explicitly consider the interlinkages with ecosystems from WEF-Nexus sectors.

Land is acknowledged as part of the Nexus in several publications and frameworks ([15], [17], [18], [19], [20], [21], [23], [24], [25], [28], [29], [30], [31], [35], [37], [39], [42], [44]). Land use as a theme was most discussed in 2011 – 2014 ([35]) or 2016 – 2018 ([27]), respectively, but not after 2018 ([35], [27]). Different bibliometric analyses describe land(use) as one of the top keywords or trends ([57], [60]). Seven frameworks in Table 7 explicitly consider the interlinkages with land(use) from WEF-Nexus sectors.

Also, other categories are mentioned, however more sporadically. Some mention Nexus Frameworks or studies that include waste as one aspect of integration ([17], [27], [42], [60], [66], [72], [73]). Some describe that waste is neglected and must be included in a WEF-Nexus ([20]), argue to include waste to the WEF-Nexus ([30], [41]) or that, among others, a WEF-Nexus shall incorporate a waste management perspective ([40]). Bibliometric analyses identify waste in the nexus discussions but not as major trends or top keywords ([27], [60], [66]). The WSW-Nexus is one framework in Table 7 that explicitly includes waste.

Some mention the importance of health in the Nexus ([35], [38]). [35] show the appearance of health in the Nexus literature after 2019. Health is seen as one major social issue by [26] and one framework is proposed that puts health at the heart of the WEF-Nexus (Nuwayhid and Mohtar 2022).

This shows that it is widely discussed in literature that other categories are integrated with the WEF-Nexus to various degrees, and depending on the context in which the Nexus is applied. Therefore, at this stage of maturity in developing the WEF-Nexus, it appears most sensible to conclude that the WEF-Nexus integrates water, food, energy, and other related categories or systems. This is done in some documents speaking of water, energy, food, and „other linked sectors" in [18, p. 208], „other related systems" ([26, p. 2]) or „any other component relevant to the research objective" ([68, p. 7]).

In Table 9 the categories above are subsumed in the group of *integrated sectors and systems*. Besides these systems and sectors that are integrated, the literature points out several other aspects that should be integrated as shown in Table 9 and subsumed in a group that can best be named *integrated implementation*. First and foremost, policy, management, and governance shall be integrated when the goals of the Nexus are to be achieved. In applying the Nexus, integrated planning, decision-making, assessments, and strategies are mentioned.

In a third group named *integrated methods*, authors call for integrated models, tools, indicators, data, platforms, and methods to be integrated. Furthermore, science-policy integration is needed. Integration of social sciences into the currently more dominant natural sciences research field is often mentioned.

Table 9: *Overview of all aspects that should be integrated within the WEF-Nexus. They are grouped into the three groups: "integrated sectors and systems", "integrated implementation" and "integrated methods". Source: Own representation.*

Categories of Integration	***Description and Sources***
Integrated Sectors and Systems	
Water, Energy, Food	*In the framework: most frameworks (due to focus on the WEF-Nexus of this study).*
	In analyzed documents: [15], [16], [17], [18], [19], [20], [21], [22], [24], [25], [26], [27], [28], [29], [30], [32], [36], [37], [38], [41], [42], [44].
Climate/Emissions	*In frameworks: [B], [E], [I], [U].*

Categories of Integration	***Description and Sources***
	In analyzed documents: [15], [20], [23], [24], [25], [27], [30], [35], [36], [37], [38], [39], [42], [48], [50], [57], [58], [60], [65], [70], [72], [73].
Ecosystems	*In frameworks: [G], [O], [S], [AA], [AE], [AG]*
	In analyzed documents: [20], [23], [25], [26], [27], [30], [35], [40], [43], [49], [50], [55], [57], [60], [64], [66], [67], [68], [71], [72], [73].
Land	*In frameworks: [C], [D], [E], [Q], [S], [U], [AF].*
Land-use ***(Soil)***	*In analyzed documents: [15], [17], [18], [19], [20], [21], [23], [24], [25], [27], [28], [29], [30], [31], [35], [36], [37], [38], [39], [42], [44], [57], [60], [73].*
Waste	*In frameworks: [M]*
	In analyzed documents: [17], [20], [27], [39], [40], [41], [42], [60], [66], [72], [73].
Health	*In frameworks: [X]*
	In analyzed documents: [26], [35], [38], [39], [72], [73].
Integrated Implementation	
Policy	*[16], [17], [19], [20], [21], [25], [27], [28], [34], [35], [37], [38], [39], [42], [44], [50], [55], [58], [62], [63], [66], [69], [70], [71], [73].*
Management	*[18], [21], [24], [28], [30], [31], [32], [35], [36], [37], [38], [39], [41], [55], [57], [63], [68], [70].*
Governance	*[16], [19], [27], [28], [30], [35], [38], [39], [44], [57], [63], [68], [71].*
Planning	*[19], [25], [26], [28], [30], [33], [37], [42], [50], [62], [68].*
Decision-Making	*[26], [28], [33], [37], [40], [52], [55], [67], [68], [70].*
Assessment	*[23], [36], [37], [60].*
Strategies	*[35], [37], [38], [58].*
Implementation	*[30], [37].*
Integrated Methods	
Models	*[23], [30], [31], [32], [35], [37], [38], [39], [40], [42], [46], [49], [52], [58], [68], [69], [70], [71].*
Methods	*[16], [30], [33], [38], [45], [55], [59].*
Social Sciences	*[23], [58], [59], [63], [64], [67].*
Indicators	*[16], [24], [28], [31], [42].*
Data	*[28], [51], [63], [65], [68].*
Science-Policy	*[15], [19], [21], [73].*
Tools	*[37], [44].*

Only topics that were mentioned more than once are shown here.

3.3.2.4 Features

Table 10 presents the features of the Integrated Management Approaches and the WEF-Nexus from the first research phase, as well as an examination of the WEF-Nexus features in the literature of the second research phase.

The analysis shows that the features of the WEF-Nexus continue to be part of the scientific debate and the description of the Nexus. This is not surprising since it was not expected that the WEF-Nexus will undergo a fundamental change in its goals and features in the past eight years. However, some relevant changes in the features appeared as the WEF-Nexus has matured.

Some eight fundamental features of the WEF-Nexus that have been described in its earlier days are widely confirmed in more than 30 analyzed documents. They are that the Nexus *brings together sectors*, *aims to reduce trade-offs* and *increase synergies*. It further *provides different methods and tools for assessment.* It *considers governance, norms, institutions, and organizations*, aims at *holism*, *complexity,* and *interdisciplinary*, and embraces *participation and inclusion of stakeholders*. Four additional features of the Nexus are confirmed in recent literature, yet in fewer than 30 documents. They are that the WEF-Nexus is a *systems approach*, is *transdisciplinary*, *promotes partnering with the private sector to improve Nexus-based investments* and focuses on *systems efficiency*.

Some features have been described for the WSW-Nexus or the integrated approaches in the past, but not for the WEF-Nexus. They are clearly now also features of the WEF-Nexus as shown in recent literature. To *embrace complexity* and *uncertainty*, to *consider different scales* and to *combine different modelling approaches* are confirmed as WEF-Nexus features in several of the documents. Mentioned by only a few sources is the *aim for local impact*, *consideration of local context* and *economic incentives*.

In Roidt & Avellán (2019) we have described features for some of the Integrated Management Approaches that are specific to one approach and are therefore not reflected in the WEF-Nexus. To *reform governance arrangements* as feature of IWRM is also partly described for the WEF-Nexus. It is, however, subsumed under the feature to *consider governance, norms, institutions, and organizations*. The feature of ISWM to *strengthen legislation and policy* is similar to the goal of the WEF-Nexus to *enhance policy coherence*.

One feature of the WEF-Nexus, as initially described by Hoff (2011), is the *focus on the poor*. It hardly received any recognition or confirmation in the analyzed literature. Liu et al. ([44]) mention poverty as one *related theme* of the WEF-Nexus without further going into detail. On the contrary, Hejnowicz et al. ([39]) note that some authors argue that the security framing of the WEF-Nexus prioritizes the focus on economic interests over the interests of the poorest. One must therefore conclude that the direct focus on the poor cannot be seen as a feature of the WEF-Nexus.

In conclusion, the methodology of this analysis does not allow for a final decision on which of the features can be considered part of a WEF-Nexus or not. However, a dozen features are described in more than one-third of the analyzed documents on the WEF-Nexus in research phase 2. Therefore, the following features from Table 10 are considered here as the main WEF-Nexus feature:

- Reduce trade-offs and increase synergies.
- Consider different scales
- Bring together sectors
- Embrace complexity
- Holism
- Combine different modelling approaches.
- Consider governance, norms, institutions, and organizations.
- Provide methods and tools for assessment.
- Participation and inclusion of stakeholders
- Interdisciplinarity
- Focus on systems efficiency.
- Transdisciplinarity

Table 10: *Features of the Integrated Management Approaches and the WEF-Nexus of research phase 1 (presented in Roidt & Avellán (2019), as well as research phase 2, including all sources in which the respective feature was mentioned. For an easier overview, the last column shows the number of citations for research phase 2. Source: Expanded from Roidt & Avellán (2019, p. 613).*

Features	***ISWM***	***INRM***	***IWRM***	***WEF-Nexus phase 1***	***WEF-Nexus phase 2***	***No. of sources phase 2***
Reform governance arrangements			*X*			-
Strengthen legislation and policy.	*X*					-
Community-based activities and governance		*X*				-
Consider governance, norms, institutions, and organizations.				*X*	*[15], [16], [18], [19], [20], [21], [22], [23], [26], [27], [28], [29], [30], [31], [33], [35], [37], [38], [39], [43], [44], [46], [48], [57], [59], [60], [61], [63], [64], [66], [68], [69], [70], [73].*	*34*
Holism	*X*	*X*	*X*	*X*	*[15], [17], [18], [20], [21], [23], [24], [26], [27], [28], [29], [30], [35], [37], [38], [39], [40], [42], [43], [44], [46], [47], [50], [52], [56], [57], [58], [60], [63], [64], [68], [69], [70], [72], [73].*	*35*
Systems Approach	*X*	*X*	*X*	*X*	*[18], [19], [21], [23], [27], [28], [30], [37], [38], [39], [40], [47], [67], [73].*	*14*
Participation and inclusion of stakeholders	*X*	*X*	*X*	*X*	*[16], [17], [18], [19], [21], [23], [26], [27], [28], [29], [31], [32], [35], [37], [38], [39], [40], [43], [45], [46], [47], [48], [57], [58], [61], [64], [68], [69], [70], [71], [72], [73].*	*32*
Embrace complexity	*X*	*X*	*X*		*[17], [18], [19], [20], [21], [22], [23], [24], [26], [28], [30], [32], [35], [38], [39], [40], [41], [42], [43], [44], [45], [47], [48], [49], [51], [52], [53], [54], [55], [56], [57], [58], [59], [63], [64], [66], [69], [73].*	*38*
Embrace uncertainty		*X*	*X*		*[18], [19], [32], [36], [37], [39], [44], [54], [58], [62].*	*10*

Features	***ISWM***	***INRM***	***IWRM***	***WEF-Nexus phase 1***	***WEF-Nexus phase 2***	***No. of sources phase 2***
Interdisciplinarity	*X*	*X*	*X*	*X*	*[15], [16], [17], [18], [19], [20], [21], [27], [28], [30], [35], [36], [37], [38], [39], [40], [44], [46], [47], [48], [52], [53], [54], [55], [57], [58], [59], [60], [64], [67], [69], [73].*	*32*
Transdisciplinarity		*X*	*X*	*X*	*[18], [19], [21], [23], [27], [28], [29], [30], [38], [39], [44], [48], [53], [58], [59], [61], [62], [64], [67], [69], [73].*	*21*
Consideration of local context	*X*	*X*			*[21], [27], [28].*	*3*
Aim for local impact.	*X*	*X*			*[17]*	*1*
Research paradigm		*X*				*-*
Increase adaptive capacity		*X*				*-*
Based on efficiency and equity			*X*			*-*
People-centered		*X*				*-*
Bring together sectors				*X*	*[15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37], [38], [39], [40], [41], [42], [43], [44] [46], [47], [58], [65], [67], [68], [69], [70], [71], [72], [73].*	*41*
Focus on the poor				*X*	*[44]*	*1*
Multiple scales of analysis and scaling up and out		*X*				*0*

Features	***ISWM***	***INRM***	***IWRM***	***WEF-Nexus phase 1***	***WEF-Nexus phase 2***	***No. of sources phase 2***
Consider different scales					*[15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [35], [36], [37], [39], [40], [42], [43], [44], [47], [48], [49], [51], [52], [53], [54], [55], [57], [58], [63], [64], [66], [67], [71], [72].*	*43*
Reduce trade-offs and increase synergies.				*X*	*[15], [16], [17], [18], [19], [20], [21], [23], [24], [25], [26], [27], [28], [30], [31], [34], [35], [36], [37], [38], [39], [40], [41], [42], [43], [44] [45], [46], [47], [48], [49], [50], [55], [58], [59], [61], [62], [63], [66], [67], [68], [69], [70], [71], [73].*	*45*
Focus on systems efficiency.				*X*	*[15], [17], [18], [19], [20], [21], [22], [28], [29], [30], [31], [32], [34], [35], [36], [37], [38], [39], [42], [46], [47], [48], [62], [63], [67], [68], [71].*	*27*
Promote partnering with the private sector to improve Nexus-based investments.				*X*	*[32], [35], [39], [43], [62], [63], [67], [72].*	*8*
Provide methods and tools for assessment.				*X*	*[15], [16], [17], [18], [19], [21], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [35], [36], [37], [39], [40], [42], [44], [46], [48], [54], [57], [59], [60], [67], [69], [73].*	*33*
Combine different modelling approaches.					*[15], [16], [17], [18], [19], [20], [21], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [35], [36], [37], [38], [39], [40], [42], [44], [45], [46], [51], [52], [53], [58], [67], [69], [73].*	*35*
Economic incentives			*X*		*[22], [28], [43].*	*3*

Since the initial description of the WEF-Nexus, new features have been described that did not appear in its early days. They are categorized here into three new features called *Nexus indicators*, *incorporating the political and social dimension* and *innovation*.

Nexus indicators: The analyzed documents do not provide evidence that there is a universal Nexus indicator or set of indicators that is commonly accepted and applied. Yet several authors argue that the development of indicators is beneficial to the Nexus ([22], [26], [38], [43]) or describe the growing interest and role of indicators in the Nexus ([29], [35], [39], [42]). While here the term WEF-Nexus indicators is used, they are referred to either as indicator ([22], [29], [35], [38],[67]), index ([16], [34], [42], [72]) or metrics ([26], [38], [39], [67]).

An example is the WEF-Nexus Index at the country scale as a combination of 21 globally available water-, energy- and food indicators that is mentioned in [16] and [35] but developed in Simpson et al. (2022).

[34] and [42] mention the Pardee RAND Food-Energy-Water Security Index that was developed by Willis et al. (2016) which is based on several sectoral sub-indices. The indicator is available at the country scale in an online interactive map (RAND, 2023).

Several other indicators were mentioned in the analyzed documents yet were not picked up by other authors. They are:

- Synergy indicators for water use, energy, and food production in [35] by (Hua et al., 2023).
- WEF-Nexus Index for dairy farms developed in Entrena-Barbero et al. (2023) and mentioned in [35].
- WEF-Nexus Index for Latin America and the Caribbean was developed by Mahlknecht and González-Bravo (2018) in [42].
- Nexus City Index by Schlör et al. (2018) in [42].
- Nexus Security Index, including water, energy, food security, as well as disaster risk and climate change, developed by [72].

Incorporating the political and social dimension: Since its initial description, the WEF-Nexus aimed at improving governance, tackling policy coherence and focusing on interdisciplinary research. Yet Nexus literature often remained focused on the analysis of biophysical interlinkages of the WEF systems through natural – rather than social – sciences. The analyzed documents show a shift that is summarized here as a key feature to *incorporate the political and social dimension*.

Some argue that a WEF-Nexus Framework must consider and analyze power structures ([16], [17], [19], [37], [39], [71]), political systems ([16], [19]) as well as social and political aspects and contexts ([21], [25], [28], [37], [40], [50], [70]). As mentioned in Chapter 3.3.2.1, Allouche ([19]) prominently contrasts the two traditions of Nexus research, where the *complex systems thinking approach* is the dominant approach in contrast to a *critical social sciences* approach that revolves around power relations, inequality, and vulnerability. Some also criticize that the social and political dimensions are still underdeveloped in the Nexus ([35], [64]). To accommodate this, authors call for the integration of social sciences to provide these perspectives ([19], [21], [48], [67]), and some describe the increase in social sciences methods in Nexus research ([23]). Other, more specific aspects mentioned in the analyzed literature shall also be subsumed under this feature since they are part of a political and social dimension of the Nexus. This includes the importance of addressing social justice, just transition and human rights ([39], [69]), poverty, inequality, and violence ([26]), migration/displacement and gender ([15], [16], [26], [39], [58]) as well as livelihoods ([20], [26], [65], [68]).

Table 11: *Three new features revealed in research phase 2, including subcategories depending on the context in which the analyzed documents describe the feature. Source: Own representation.*

New Features of the WEF-Nexus	***Sources Research Phase 2***
Nexus Indicators	
Develop Nexus indicators (metrics or indices)	*[16], [22], [26], [29], [34], [35], [38], [39], [42], [43], [45], [48], [67], [72].*
Incorporate political and social dimensions.	
Consider political aspects/processes through social sciences.	*[16], [17], [19], [21], [23], [25], [28], [35], [37], [39], [40], [48], [67], [70].*
Justice/Power/Human Rights/Just Transition/Poverty/Inequality/Violence	*[39], [26], [69], [71].*
Gender aspects	*[16], [39], [15].*
Migration/Displacement	*[26], [39], [58].*
Livelihood	*[20], [26], [65], [68].*
Innovation	
Innovation/New technologies	*[21], [28], [38], [37], [26], [58], [62], [64], [70].*
Digitalization (artificial intelligence, big data, digital twins, internet-of-things)	*[35], [39], [26], [37], [39], [53], [73].*
Only topics that were mentioned more than once are shown here.	

Innovation: To become an innovative approach in one form or another appears to be the third upcoming feature of the WEF-Nexus. Already Hoff (2011) described innovation as an enabling factor of WEF-Nexus. Based on a literature review, [21] describes innovation as a key feature of WEF-Nexus analytical approaches, and [28] identifies that innovation is a new feature in some Nexus approaches. Calls for innovation are mainly of a technological nature ([35], [37], [38], [58], [62], [70]). A specific focus lies on data science and technologies where several authors mention the opportunities for the Nexus, i.e., in big data ([39], [53]), artificial intelligence ([39], [26]), internet-of-things ([26]), digital twins ([35], [73]), smart systems ([35]) and others ([39], [38]). Such advancements are also subsumed under the feature of innovation. According to [68], however, the use of artificial intelligence did not reach consensus among European Nexus scholars.

3.4 Discussion

Examining the evolution of Integrated Management Approaches suggests that they have indeed contributed to preparing the ground for the WEF-Nexus.

The goals are similar among the three approaches, and the WEF-Nexus builds on them by picking up, i.e., the goal to achieve sustainability in the sectors. It then goes a step further by explicitly enhancing it to policy coherence across sectors.

The WEF-Nexus has adopted several important features of the Integrated Management Approaches, as well as the idea of a holistic view on the issues it aims to tackle. Even though the features of the WEF-Nexus are not all the same as in the three Integrated Management Approaches, the results show that several key features that have already been inherent to Integrated Management Approaches are also key to the WEF-Nexus. The WEF-Nexus, however, goes beyond what has been previously described. Features such as the explicit consideration of different scales or the focus on reduction of trade-offs and increase of synergies are exclusive to the WEF-Nexus.

The features that have been described for the WEF-Nexus in the first research phase have mostly been confirmed in the second research phase. This shows that existing features are still relevant. Due to their stable representation in WEF-Nexus literature over the past several years, it is expected that they will remain an important part as the WEF-Nexus is conceptually further developed in the next years. However, also new features have appeared in descriptions of the WEF-Nexus and hence such new features are likely to be more comprehensively described in future literature.

The rise of Integrated Management Approaches during the 1990s fostered broad acceptance of managing environmental resources and sectors in a more interconnected manner. Initially, this integration occurred within individual sectors, but with the introduction of the Nexus, it expanded to encompass cross-sectoral and cross-resource linkages. In the Integrated Management Approaches, it is most explicitly the different sectors or systems that are to be integrated. Some, however, already describe more aspects of integration in the Integrated Management Approaches. In INRM, Lal et al. (2001) argue that INRM is also about integration across different stakeholders, disciplines, and scales. Also, in IWRM, the importance of integrating the natural (water) system with the human system, which determines the state of water resources, is described (GWP, 2000). Also, the fundamental basis of the WEF-Nexus is the focus on interactions of humans with nature. This is generally stated by Endo et al. (2018) or de Andrade Guerra et al. (2021) and described in detail through the concept of social-ecological systems (Ali & Acquaye, 2024; Anandhi et al., 2023; Bigolin et al., 2025; Lalawmpuii & Rai, 2023; Rhouma et al., 2024). The most detailed description of the interaction between social-ecological systems and the WEF-Nexus is provided by Lucca et al. (2025). Many of the analyzed documents, however, consider this implicitly by describing human-nature interactions by the impacts of population growth, economic growth and increased prosperity directly or via climate change on water, energy, and food resources and thus also ecosystems.

Regarding integration, the study shows that integration in the WEF-Nexus is much more than just the *sectors or systems* of water, energy, and food. It is described that a WEF-Nexus also needs what is summarized under the categories of *integrated implementation* and *integrated methods*.

The results also show that the description and development of the WEF-Nexus is ongoing. It is still too early to conclude on a final definition of a WEF-Nexus. Yet the contributions towards a definition are recent and ongoing. The features, the understanding of integration and the conceptual clarity on some terms as results of these analyses form a small contribution towards a definition in that ongoing process.

If the WEF-Nexus is to be a fully described implementation framework, the specifics on integration must be clarified and defined. A starting point could be applying the *categories of integration* concept suggested in Chapter 3.3.1.4. While this study clarified the *aspects* of integration, the *interlinkages* between the aspects would describe the specifics. These interlinkages can be biophysical (e.g., evapotranspiration, infiltration), or technical (e.g., energy for groundwater pumping of irrigation water), legal (e.g., different sectoral policies), political (e.g., infrastructure plans) and many more.

Countless biophysical, technical, legal, economic, social, and political interlinkages exist between the sectors that differ for each context and scale. A WEF-Nexus Framework would consider the relevant interlinkages tailored to each context and scale.

The analysis showed that ecosystems are present in the discussion for integration under the WEF-Nexus. It appears that this is increasing more than other aspects. Especially, Lucca et al. (2025) provide a recent and detailed analysis on how nature and the WEF-Nexus are integrated. They provide a forward-looking conceptualization of a WEFE-Nexus. In addition, different Nexus projects in Europe are applying a WEFE-Nexus (i.e., NEXOGENESIS, WEFE4MED and NEXUS-NESS). The literature research methodology of this dissertation was designed towards the WEF-Nexus and not the WEFE-Nexus. Thus, the hypothesis that the WEF-Nexus is increasingly moving towards a WEFE-Nexus in research and implementation cannot be answered with certainty. This hypothesis should be analyzed in a follow-up study. In Chapter 5, an outlook into further research towards this goal is described.

The differentiation between the goals, features, and integration in the WEF-Nexus cannot be drawn very precisely, and some overlaps exist. This becomes clear when looking at *policy* in the WEF-Nexus. The goal is to enhance policy coherence in the respective sectors, while policy is also a key aspect that needs to be integrated. To consider *governance, norms, institutions, and organizations* is a feature, while integration of *governance* is also often mentioned. The same goes for the feature of *providing methods and tools for assessment* and the integration of *tools, methods, and models*. Such aspects do not belong to one category exclusively and can appear in different categories of the analysis due to the often wide and differentiated meaning of the terms.

This analysis also has some limitations. One lies in the methodology of selecting conceptual articles. It was defined what is understood by *conceptual*, yet there is no hard criterion based on which conceptual articles are selected. Even though a rigid and transparent methodology is followed, the selection of conceptual articles remains in the judgment of the author. The review of titles and abstracts by another person could lead to the selection/exclusion of one or the other article, hence altering the final selection of the conceptual articles. However, due to the high number of selected articles (73) and the large time span (1990 – 2024), the results are robust even if selection by another person would slightly differ.

Defining research on the WEF-Nexus is progressing fast, with roughly eight new articles every week for the first half of 2025. This work covers research until August 2025 and does not include the latest research on the WEF-Nexus that may cover new conceptual descriptions of it. In addition, the review articles selected again cover research that is some years old. Therefore, a structured literature analysis always lags by some years. The results of this analysis cover the WEF-Nexus of the past decades, and the second research phase showed that the described features of the Nexus remain relevant. It can be assumed that the results remain relevant for some time. However, it must be considered that perhaps new features or more detailed descriptions of features and integration, is being published at this very moment and in the future.

The conceptual literature that was analyzed in this part includes manifold information and examples of WEF-Nexus research, projects, modelling, assessments, etc. In short, the conceptualization of the WEF-Nexus in the past years has not only been a theoretical exercise but has also been implemented in many undertakings in research and practice. To successfully carry out WEF-Nexus assessments and realize change towards the WEF-Nexus goals, several different undertakings are needed. Participants from different sectors must be brought together, stakeholders' views must be included, policy analysis must be carried out and the context must be understood. One important basis of such assessments is the understanding and quantification of the various relevant interlinkages between the sectors. Thus, my research focus continued from the conceptual analyses of the WEF-Nexus towards a detailed analysis of such interlinkages in the year 2020.

Therefore, the last part of this dissertation provides detailed computations of the sub-annual water footprint and virtual water trade of thermal electricity generation. Such computations improve the understanding of the physical water-electricity interlinkages and thus form one further, small piece of the WEF-Nexus puzzle.

4 Part C – Computations of Interlinkages

4.1 Introduction

In the European Union (EU), the environmental impacts of electricity generation are optimized through monitoring and taxing CO_2 intensity, aiming to reduce CO_2 in the electricity mix (European Union, 2003). Production of electricity, however, also uses water resources, e.g., as cooling water in thermal power plants, i.e., nuclear, gas, and coal power plants, but also to a lesser degree in PV and wind power (Jin et al., 2019). Hence, the way electricity is produced influences the available water resources in the area where the plants are located, while the electricity might be exported and consumed in another area or country. What if electricity demand in one region results in water scarcity caused by electricity production in another region? If the respective data are available, a monitoring tool can support decision-making to reduce the electricity sector’s pressure on water resources. Understanding and managing the electricity-water nexus opens possibilities to improve water resources management through measures in the electricity sector. Therefore, this part investigates how the electricity-water nexus in Europe can be monitored and perhaps be used as a basis for a decision-making tool within a WEF-Nexus Framework.

The nexus of electricity and water can be understood with the concepts of water footprint and virtual water. The water footprint was first introduced by Arjen Hoekstra in 2002 and defined and refined in the decade thereafter (Gerbens-Leenes et al., 2020). The central works were published around this time with *The water footprint of humanity* (Hoekstra & Mekonnen, 2012) and other articles that laid the foundation of water footprint research (Gleeson et al., 2012, 2012; Hoekstra & Chapagain, 2007; Hoekstra & Hung, 2005; Mekonnen & Hoekstra, 2011, 2012).

In the *2011 Water Footprint Assessment Manual,* the water footprint is defined as “the total volume of freshwater used to produce the goods and services consumed by the individual or community or produced by the business” (Hoekstra et al., 2012, p. 194).

The water footprint is divided into three categories by Hoekstra et al. (2012):

- **Blue Water:** Water extracted from surface and groundwater resources.
- **Green Water:** Precipitation not recharging surface or groundwater but stored in the soil available for plant growth.
- **Gray Water:** Needed volume of freshwater to dilute pollutants to agreed water quality standards.

Especially when quantifying the water footprint in agricultural products, the three types of water show their relevance. While green water is the type of water that naturally occurs in rainfed agriculture, blue water must be extracted, e.g., from groundwater when used in irrigated farming and is not available anymore for other use. In conventional agriculture, pesticides, and fertilizers require gray water resources to dilute pollution (ibid.).

Whenever a product with a specific water footprint is transported regionally or internationally, i.e., through import/export, it is appropriate to speak of virtual water flows (ibid.). Hence, when different goods with a high-water footprint are exported from country A to country B, a virtual water flow is created with potential impacts on the water resources in country A based on the consumption patterns of country B. A famous example is Europe, being the largest importer of virtual water from Brazil in agricultural commodities (Da Silva et al., 2016).

4.1.1 State of the Art in Water Footprint and Virtual Water Research

Since the past decade, water footprint calculations have been widely applied to countless goods (Mekonnen & Hoekstra, 2011), companies (Forin et al., 2020), countries (Hoekstra & Chapagain, 2007) and processes (Chukalla et al., 2015) in more than 6,000 peer-reviewed articles (Scopus search “water footprint” OR “virtual water”). The most recent review paper on virtual water trade confirms that agricultural products make up the majority of global virtual water trade, influenced mainly by a few key products, i.e., livestock products, cocoa, coffee, palm oil, soybean, maize, and wheat, accounting for more than 70% of global virtual water trade (Mekonnen et al., 2024). Global trade of virtual water has almost tripled in the past four decades with China emerging as a major importer of virtual water (ibid.). Such global phenomena can be better understood with the concept of virtual water, which is used as a tool to assess water-related impacts. A key limitation of the concept to inform policy making is its narrow focus on water in traded goods and services. This neglects major factors such as capital or labor resources, which highly influence export decisions of countries (ibid.). Furthermore, the authors suggest that the concept must be expanded to not only consider consumed water volumes but also consider local water availability, societal needs and ecosystem resilience when aiming to guide policies to achieve sustainable water management (ibid.).

While water footprint and virtual water largely focus on agriculture (Mekonnen et al., 2024) it can also be applied to the electricity sector. In the case of the electricity-water nexus, the water footprint can be defined as the total volume of freshwater in m³ used to produce one kWh of electricity.

Research on the water footprint and virtual water in the electricity sector has been ongoing for the past decade, with different objectives. Three widely recognized articles tackle the consumptive water footprint of the energy sector at a global scale, both providing valuable data on water withdrawal and consumption for different countries, fuel types and water-cooling technologies (Macknick et al., 2012; Mekonnen et al., 2015; Spang et al., 2014).

Before looking into latest research, different terms and concepts must be clarified regarding the water footprint of electricity. No common standard for calculating the water footprint of electricity was found. Different studies have different scopes, often due to data availability.

Three stages can be differentiated when calculating the water footprint of electricity:

- **Fuel Supply:** Water demand to produce fuel, i.e., biomass, coal, gas, etc.
- **Construction:** Water demand to construct power plants, i.e., PV, wind turbines, thermal power plants or hydroelectric dams.
- **Operation:** Water demand for operation of the plants, i.e., cooling water in thermal power plants.

(Mekonnen et al., 2015)

The water footprint categories described above also apply to the electricity sector.

- **Green Water:** Relevant for the fuel supply of biomass but otherwise not relevant in electricity production (Mekonnen et al., 2015).
- **Blue Water:** Consumed water is mainly relevant at the operational stage in electricity production of thermal power plants, where it is lost through cooling towers. In hydropower stations with open reservoirs it is lost through evaporation (Chini et al., 2018; Spang et al., 2014).
- **Gray Water:** Dilution of heat pollution from cooling water of thermal power plants in surface waters (Hoekstra et al., 2012).

Thermal power plants use large quantities of water for cooling where – depending on the cooling technology – water is evaporated through cooling towers and or released back to the environment at a higher temperature. Hence, a differentiation between water withdrawal and consumption is necessary. It was provided by the United States Geological Survey (Kenny et al., 2005) and is presented here with a focus on the water footprint of electricity.

- **Water Withdrawal**: Blue water that is extracted from the water environment.
- **Water Consumption:** Withdrawn blue water that is evaporated or otherwise removed from the water environment during electricity production.

Thermal power plants use different cooling technologies with different water withdrawal and consumption rates. Plants with once-through cooling withdraw large quantities of water, take up excess heat from power plants and release it back to the water environment at a higher temperature. On the one hand, blue water withdrawal is very large, while blue water consumption is minimal. On the other hand, the gray water footprint is large due to the high thermal pollution of the nearby water environment. Power plants with cooling towers circulate water through the tower, where parts of the cooling water are evaporated, while the other part is cooled through the effect of evaporative cooling. Here, blue water consumption due to evaporation is high, while withdrawal is relatively low and only makes up for the evaporated quantities. Furthermore, gray water is usually not generated in this cooling system (ibid.).

In a comprehensive article, Macknick et al. (2012) provide an overview of water withdrawal and water consumption for each electricity production technology and each cooling system.

The latest available global meta-analysis on water use for electricity generation was published in 2019, with an overview of blue water consumption over the total life cycle. The main result is shown in Figure 16, which aims to give an overview of the large variety of values per technology. Values vary depending on the chosen boundary of the analysis, country, cooling technology, etc. An exceptionally high variety is given for hydropower, where low water consumption is the case in run-of-river plants, but high water consumption happens at stored hydropower due to sometimes large evaporation from dams (Jin et al., 2019).

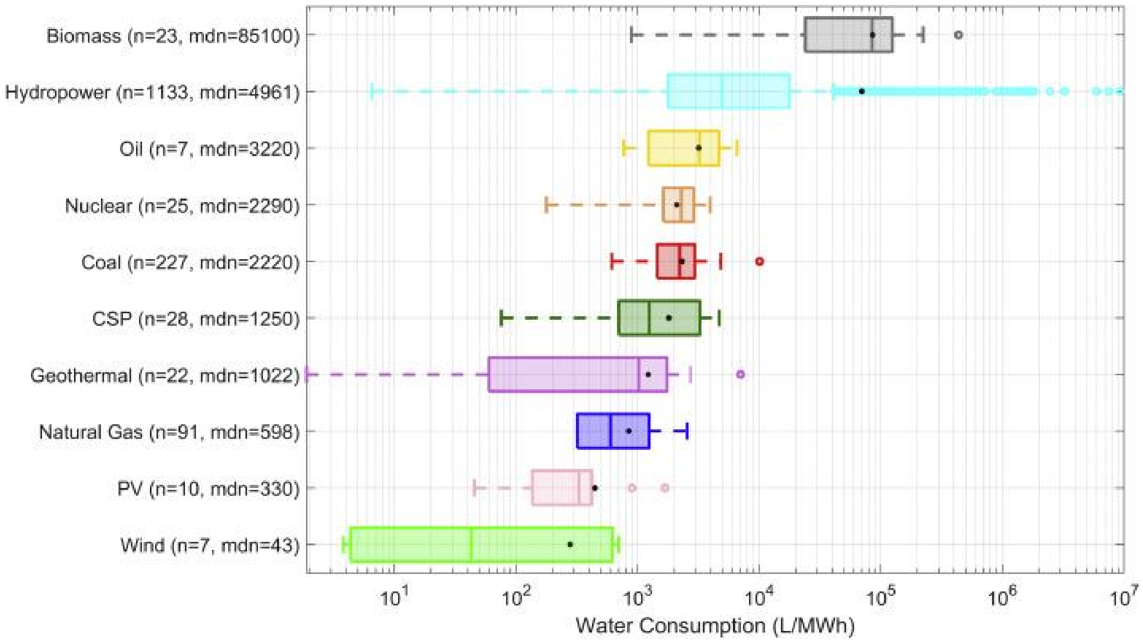


Figure 16: *Graph showing the specific water consumption of different electricity production types. Values are shown as boxplots representing the range of values gathered in a meta-study. Consider that the X-axis is logarithmic. Source: (Jin et al., 2019, p. 2), reproduction of graph with kind approval by the author.*

Analysis of the electricity sector´s water footprint and virtual water trade is recently been studied for different countries, e.g., the USA, with a focus on blue and gray virtual water transfer networks (Chini et al., 2018), or on future scenarios (Graham et al., 2021).

The water footprint of electricity generation was also studied in Ecuador, with the specific focus on how it changes based on water availability in the country at a sub annual temporal scale. Vaca-Jiménez et al. (2019) show that low water availability results in less hydropower generation with a high blue water footprint, leading to a more water efficient electricity generation, however, utilizing fossil fuels.

In China, a study shows the inter-provincial virtual water trade of electricity and how it developed between 2006-2016. It reveals how regions in the east of China with high energy demand (Beijing-Tianjin-Hebei region) contribute to water stress on the other side of the country (West Inner Mongolia and Ningxia). However, the fast growth of wind and PV in China´s electricity mix slowed the increased pressure on water resources by the electricity sector (C. Zhang et al., 2020).

The first consumptive water footprint of the European energy sector was provided at a high spatial resolution by Vanham et al. (2019), suggesting that water footprint calculations shall inform European energy policy making. A specific focus on electricity production and virtual water trade in Europe is, however, not included. This is provided by Larsen & Drews (2019), who studied the water use of electricity production and its changes over the long term (1980–2015) for Europe. Lohrmann et al. (2021) project a decrease of Europe's electricity water footprint of up to 28.3% until 2025 if the electricity mix is 100% renewable. Mapes & Larsen (2023), investigate water consumption and withdrawal of electricity production in Europe with a specific focus on the water footprint of concentrated solar power (CSP) and carbon capture and storage (CCS). Regarding trade, electricity trade in Europe was investigated by Abrell & Rausch (2016); however, there was no focus on its water footprint. This was provided in 2020 with an overview of the virtual water trade of electricity generation for 2010 and 2017, showing an increasing trend in virtual water trade (Chini & Stillwell, 2020).

4.1.2 Research Deficit

Aiming to understand the electricity-water nexus globally but also in Europe is not new, and a few studies – as shown above – have been devoted to the topic. The research shows that data availability is promising to carry out more detailed analysis, yet the studies do not describe how data can be utilized to systematically and continuously monitor the dynamics of Europe's power sector water footprint. Studies also do not consider sub-annual dynamics of electricity demand and generation, and related water footprint. In spring 2020, a unique chance to study such sub-annual dynamics appeared when the COVID-19 pandemic hit Europe. In response, all European countries imposed strict lockdowns or similar measures (here referred to as lockdown-like measures) to reduce the spread of the virus. This resulted, among others, in a reduction of flights to/from Europe (Holroyd, 2020), school closures in most regions (UNESCO, 2020), and a general reduction of economic activities (Ewing, 2020). Especially the latter, caused electricity demand to reduce, i.e., by 18% in Italy one week after the lockdown (Cicala, 2020). How exactly electricity demand and generation changed in Europe and how this is related to electricity's water footprint and virtual water trade was not studied so far, and resulted in the following objectives in Roidt et al. (2020b).

4.1.3 Objectives

The detailed objectives of this chapter are as follows:

- How did lockdown-like measures during the COVID-19 pandemic impact electricity generation and the related water footprint of thermal power plants in Europe?
- How was the related virtual water trade in Europe affected by these measures?

The European countries with the highest COVID-19 numbers in April 2020 – Germany, Italy, France, Spain, and Switzerland – are also direct neighbors and electricity trade partners. This made it possible to investigate changes in virtual water trade among these countries.

This research therefore answers the overall objective of this part as formulated in Chapter 1 (Provide the computation of interlinkages at the nexus of water and electricity in Europe).

4.2 Methods and Materials

In March 2020, most European countries implemented quarantine- and lockdown-like measures starting on March 10, 2020, with Italy. Table 12 gives an overview of the five countries in focus.

Table 12: *Dates on which the countries announced first precautionary measures with regards to the corona virus and later lockdown measures. The dates were gathered from media coverage. Switzerland and Spain directly announced lockdown measures with no previous precautionary measures. Source: (Roidt et al., 2020b supplementary material).*

Date	***France***	***Germany***	***Switzerland***	***Italy***	***Spain***
Precautionary Measures (PCM)	*12-Mar-20*[1]	*15-Mar-20*[2]	--	*20-Feb-20*[3]	--
Lockdown Measures (LDM)	*24-Mar-20*[4]	*23-Mar-20*[5]	*16-Mar-20*[6]	*10-Mar-20*[3]	*16-Mar-20*[7]

Sources: [1](Barbière, 2020), [2](Ernst & Schulte von Drach, 2020), [3](Cicala, 2020), [4](The local, 2020), [5](RTL, 2020), [6] (Swissinfo, 2020),[7](Keeley, 2020).

To examine whether Europe experienced any changes in its electricity generation during this time, we first analyzed the daily electricity generation between January 1, 2020, and April 19, 2020. We then compared this data to the average values recorded during the same period from 2016 to 2019 to assess any deviations.

Next, we calculated the consumptive water footprint related to this electricity generation. We limited the scope to the thermal power plants during their operational phase. The water footprint of wind and PV is negligible and data on hydropower are not available at the sub annual temporal resolution required. The analysis focuses on blue water consumption.

Based on *The Water Footprint Assessment Manual*, the water footprint was calculated for each country and fuel type (Hoekstra et al., 2012).

$$\mathrm{WF}_{\mathrm{c,d}} = \sum_{\mathrm{c,d}}^{\mathrm{f}} \mathrm{i}_{\mathrm{f}} * \mathrm{e}_{\mathrm{f}} \qquad (2)$$

Where:

WF = water footprint [m^3/MWh]

i_{f} = water intensity [m^3/MWh]

e_{f} = daily electricity generation [MWh]

c = country [-]

d = day [-]

f = fuel type [-]

The water intensity values (i_{f}) by Macknick et al. (2012) are used.

The other part of the analysis focused on virtual water (VW) trade between the five countries. Virtual water is calculated as the portion of WF imported and exported by each country. This is calculated as

$$\mathrm{VW}_{\mathrm{c,d}} = \frac{\mathrm{x}}{\mathrm{g}} * \mathrm{WF} \qquad (3)$$

Where:

VW = virtual water [m^3]

x = exported electricity [MWh]

g = generated electricity [MWh]

WF = water footprint [m^3/MWh]

c = country [-]

d = day [-]

For the assessment, electricity data were sourced from the European Network of Transmission System Operators for Electricity (ENTSO-E) Transparency Platform, which provides datasets with hourly or sub-hourly time resolutions for most European countries at the national level. The study utilized data from the past five years covering load, generation by type, and physical flows across 25 European countries. Regarding data processing, variables were aggregated to daily values and adjusted to ensure alignment between 2020 dates and corresponding weekdays from previous years. To assess temporal changes, the average values of the analyzed variables for 2020 before and after the implementation of lockdown measures were compared against baseline values derived from the same variables' averages from 2016 to 2019 (see Roidt et al. (2020b) for details).

Lastly, data on COVID-19 case numbers were obtained from Johns Hopkins University (JHU, 2020).

4.3 Results

The first result, shown in Figure 17(a), visualizes the electricity generation in Europe in red. The typical pattern of workweek/weekend is visible with considerably higher electricity generation needed during the week, mainly for industrial production. As the COVID-19 cases rapidly increase and lockdown measures are in place, the electricity generation drastically decreases to a weekend level in April 2020. This shows that industrial and business electricity demand has reduced, while outweighing a possible increase in power demand of private homes.

Similar to electricity, the related water footprint in Figure 17(b) decreases with reduced electricity generation. After the lockdown-like measures, the water footprint in Europe is decreased by 21% compared to the baseline years 2016 – 2019. This effect, however, is dampened. This is mainly related to a change in the energy mix, which is already visible before March 2020. The water footprint is generally lower than in the baseline years due to a change in the electricity mix, where water-intensive thermal power plant production decreased from 68.5% in the baseline years to 62.2% in 2020, prior to the lockdowns, and to 61.1% during the lockdowns, while the share of water-efficient renewables increased. While the water footprint in Europe decreased by $1.77*10^6$ m^3/day compared to the baseline, we can attribute $1.25*10^6$ m^3/day to changes in the electricity mix before 2020, $0.23*10^6$ m^3/day to changes in the electricity mix during the lockdowns and $0.29*10^6$ m^3/day to reduced electricity generation due to COVID-19.

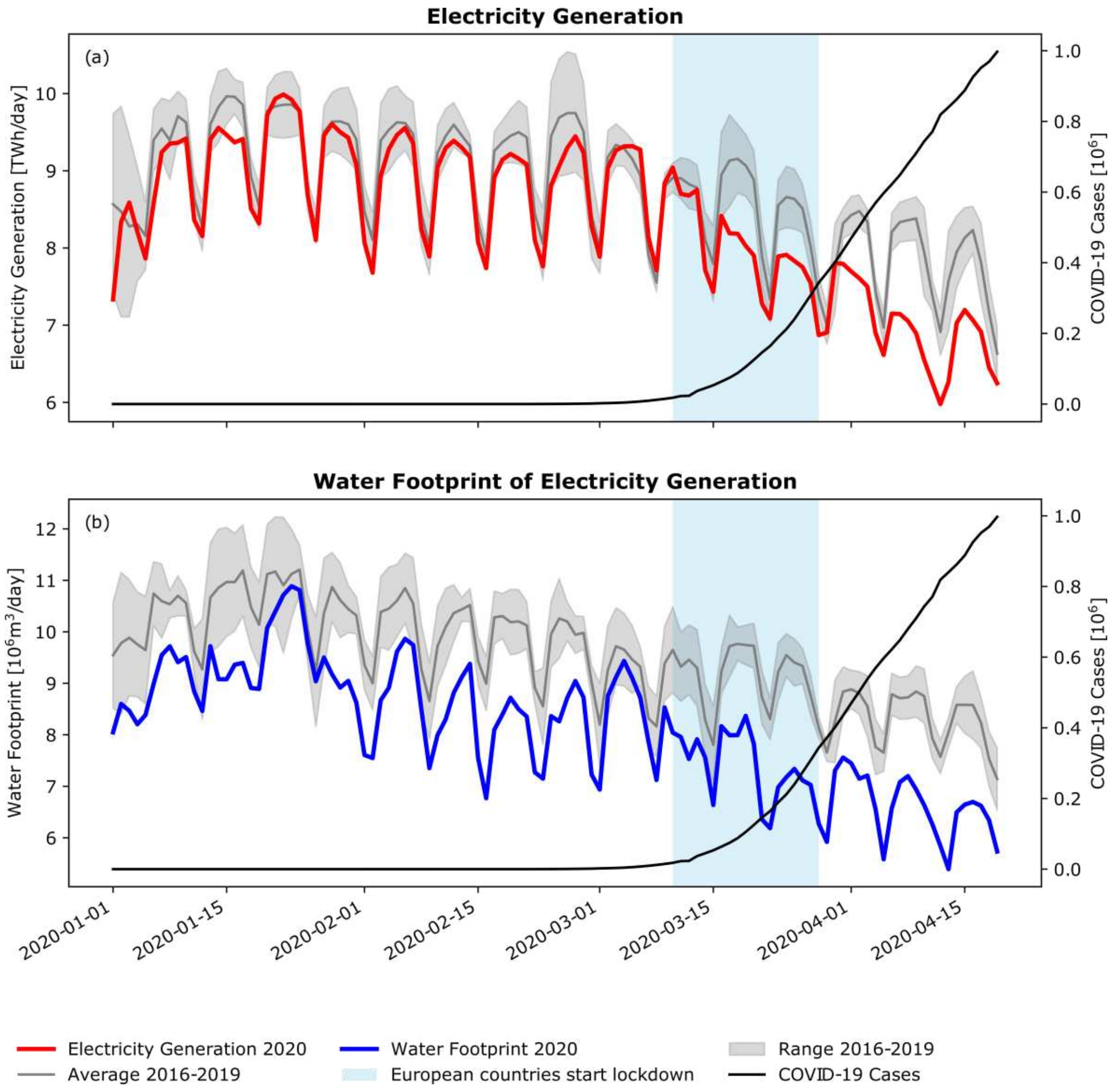
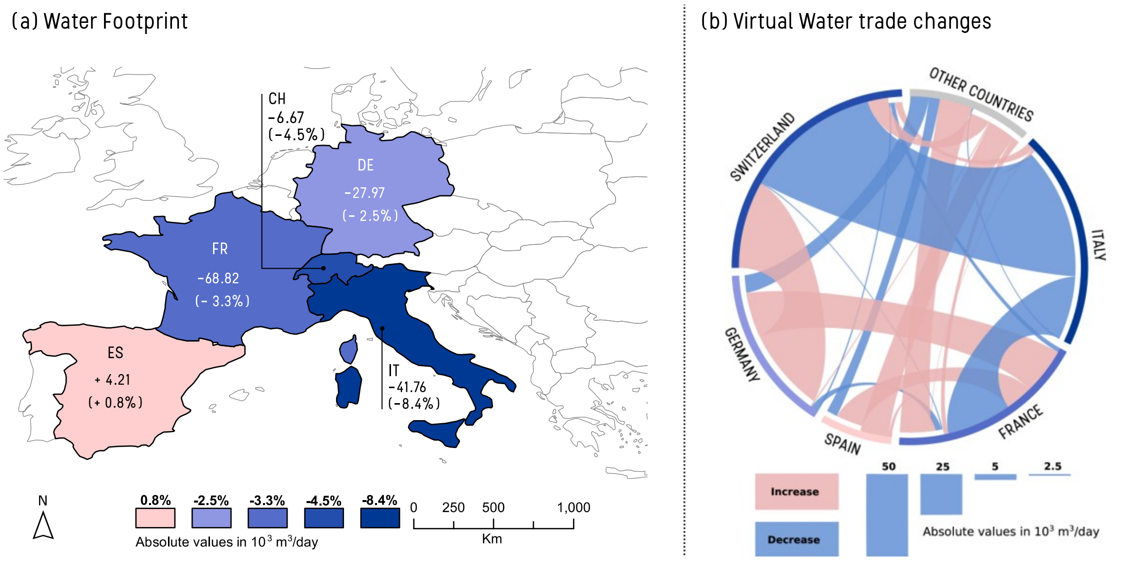


Figure 17: *Graph showing the electricity generation in Europe at the top and the related water footprint at the bottom. The red/blue line represents the data for 2020, while the gray shaded area is the range of the past years (2016 – 2019) for the same days. The dark gray line is the average of the past period. The light blue area represents the time in which countries started lockdown-like measures that correspond with the steep increase in COVID-19 cases shown in the black line. Source: (Roidt et al., 2020b, p. 685).*

The reduced electricity production in the five countries resulted in a reduced water footprint in four countries with -8.4% in Italy, -4.5% in Switzerland, -3.3% in France and -2.5% in Germany while Spain increased its water footprint by a slight +0.8%. These figures must be put into context to the trade of virtual water between the countries. Detailed graphs of electricity generation, -load, -imports and -exports as well as water footprints and virtual water trade are shown for each of the five countries in Figures 19 – 23.

A clear picture is provided by the Italian case, where electricity load (demand) dropped drastically right after the lockdown (Figure 19(c)). At the same time, Italy reduced its electricity imports (b), and thus, electricity generation (a) was reduced less drastically than its load. This reduced Italy´s domestic water footprint by 41,760 m³/day but also imports from Switzerland (-47,400 m³/day) and France (-22,800 m³/day) (see Figure 18(b) and Table 13). Italy, however, is the only country that has reduced water footprints abroad.

Germany also experienced a reduced load, reduced generation, and reduced exports of electricity while increasing imports (see Figure 21). This led to a reduced domestic water footprint, while the water footprint in France and Switzerland was increased by 16,200 m³/day and 30,500 m³/day, respectively. In other words, the German lockdowns reduced electricity demand in Germany but increased water consumption in France and Switzerland. In France and Switzerland, however, Germany´s increased demand for water was balanced by Italy´s reduced need for French and Swiss virtual water.


(a) Water Footprint

(b) Virtual Water trade changes

Figure 18: *Graphs showing water footprint and virtual water trade. Left is the variation in the consumptive water footprint of thermal power plant operations (expressed in 1,000 m³/day and percentage values). The color scale indicates changes relative to the baseline. On the right is a chord diagram illustrating virtual water transfers. Exports from each country are linked to the plot's edge, while imports are represented by a gap. Blue shading indicates a decrease in virtual water trade, whereas red shading reflects an increase. Source: (Roidt et al., 2020b, p. 686).*

Table 13: *Numerical values for Figure 18(b) of virtual water trade between the five countries. Source: (Roidt et al., 2020b supplementary material).*

	To IT	***To CH***	***To DE***	***To ES***	***To FR***	***To other***
From IT	*0*	*2.6*	*0*	*0*	*0.2*	*0.8*
From CH	*-47.4*	*0*	*30.5*	*0*	*-0.4*	*7.1*
From DE	*0*	*-0.6*	*0*	*0*	*-2.1*	*0.5*
From ES	*0*	*0*	*0*	*0*	*1.2*	*9.9*
From FR	*-22.8*	*-1.5*	*16.2*	*9.6*	*0*	*1.5*
From Others	*-0.5*	*0.2*	*-6.4*	*-3.9*	*11.5*	*0*

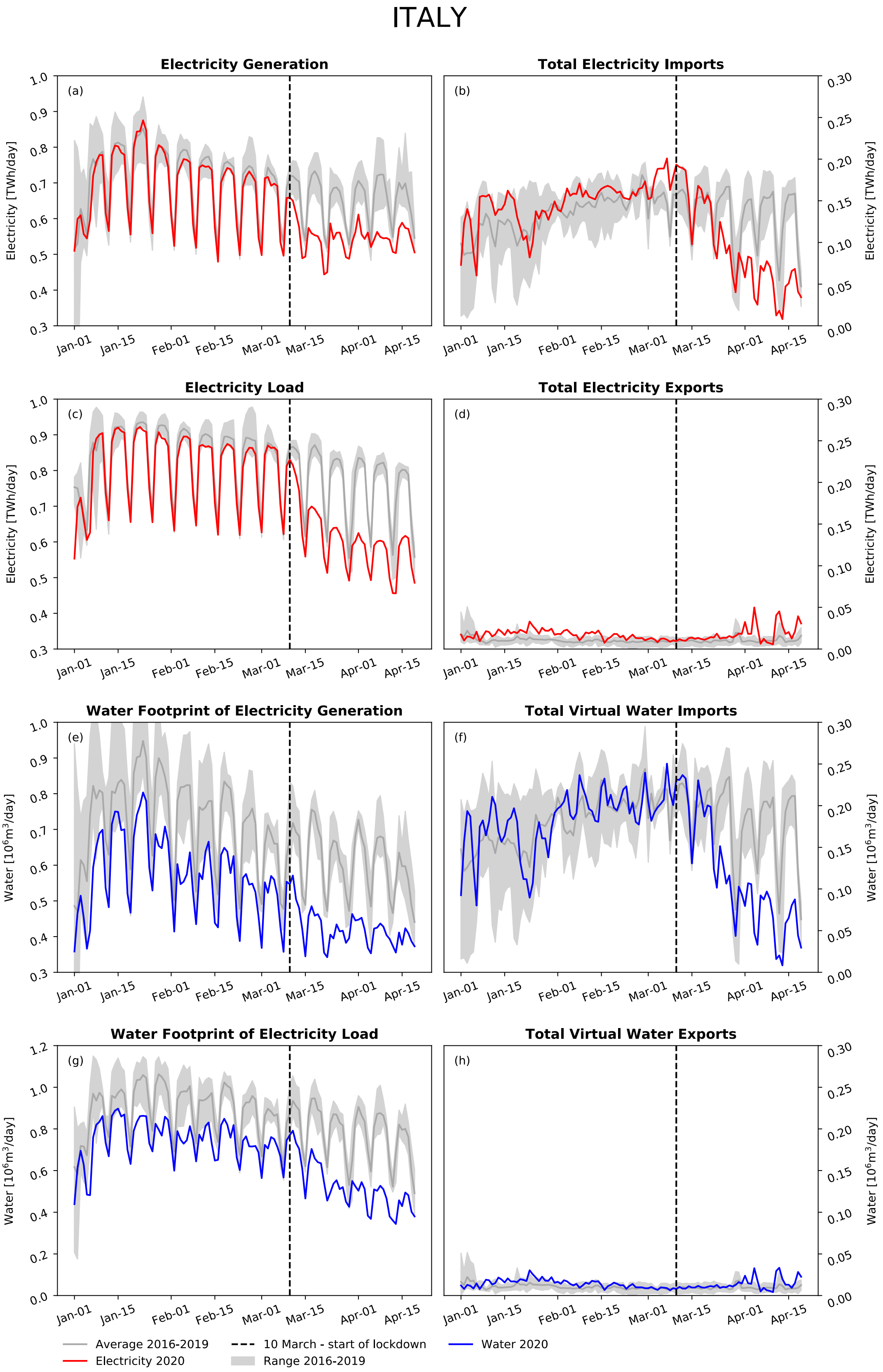


Figure 19: *For Italy, the figure shows the electricity generation (a), total electricity imports (b), electricity load (c), total electricity exports (d), water footprint of electricity generation (e), virtual water imports (f), water footprint of electricity load (g) and virtual water exports (h). Source: (Roidt et al., 2020b supplementary material).*

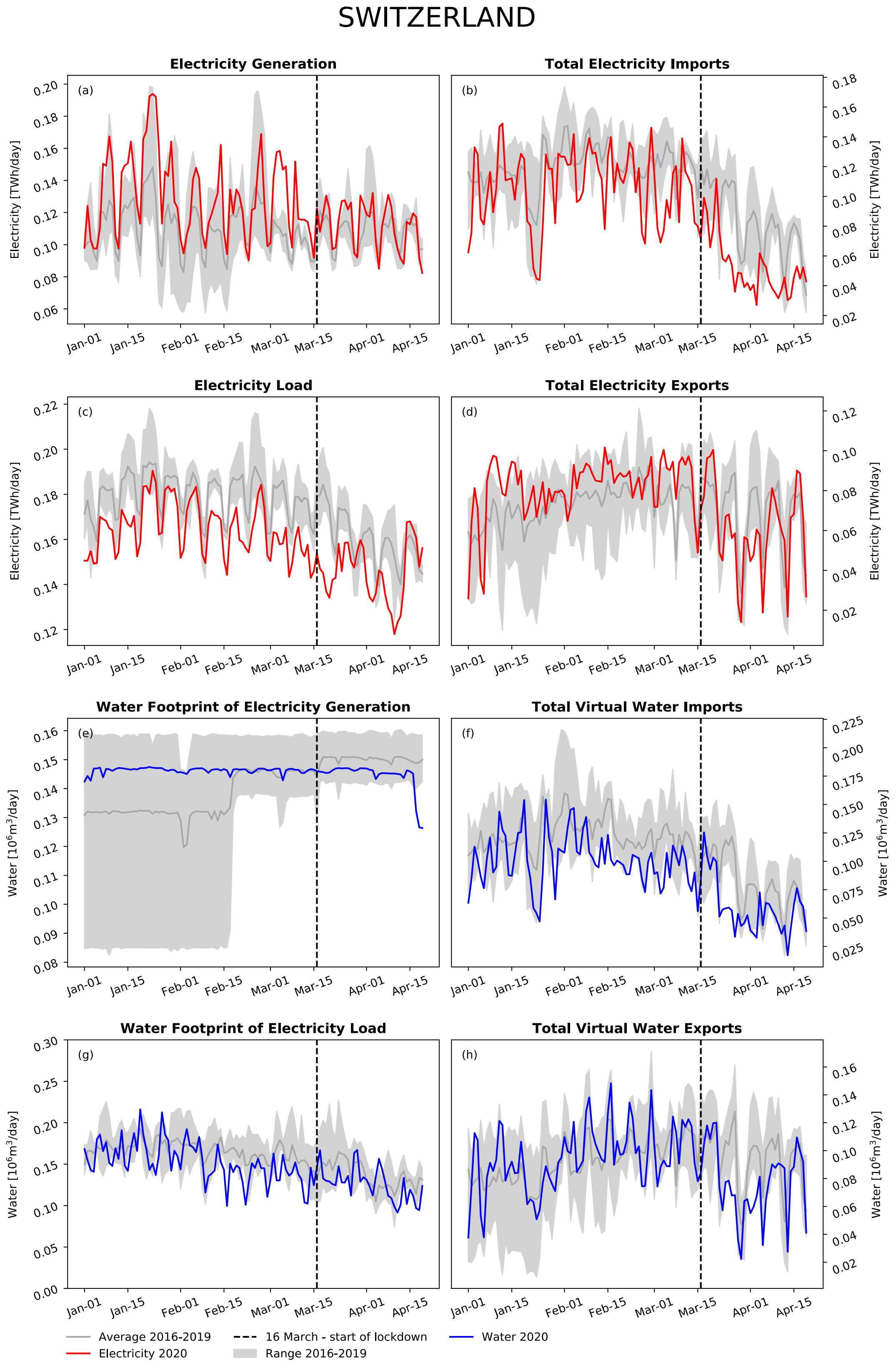


Figure 20: *For Switzerland, the figure shows the electricity generation (a), total electricity imports (b), electricity load (c), total electricity exports (d), water footprint of electricity generation (e), virtual water imports (f), water footprint of electricity load (g) and virtual water exports (h). Source: (Roidt et al., 2020b supplementary material).*

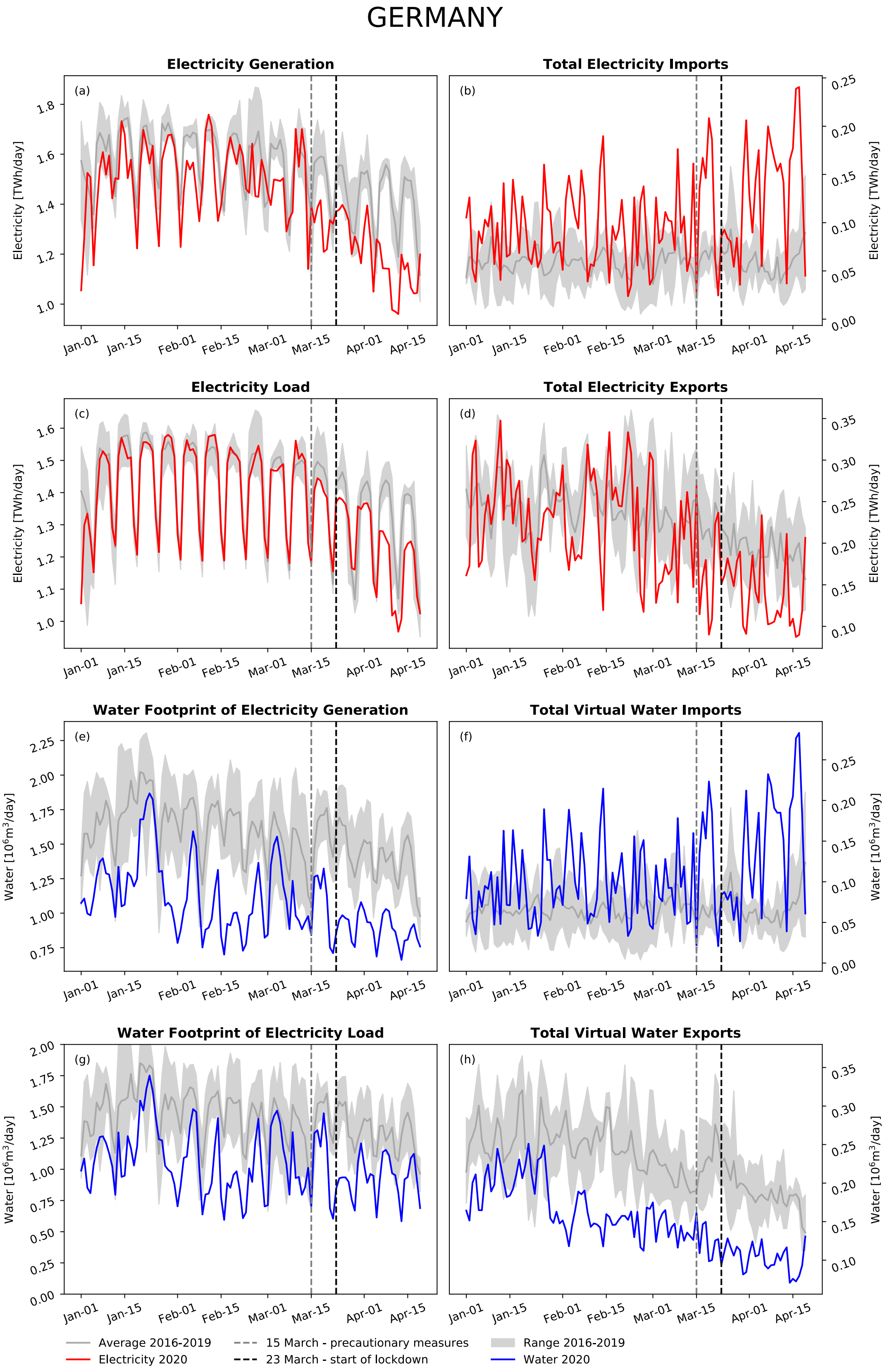


Figure 21: *For Germany, the figure shows the electricity generation (a), total electricity imports (b), electricity load (c), total electricity exports (d), water footprint of electricity generation (e), virtual water imports (f), water footprint of electricity load (g) and virtual water exports (h). Source: (Roidt et al., 2020b supplementary material).*

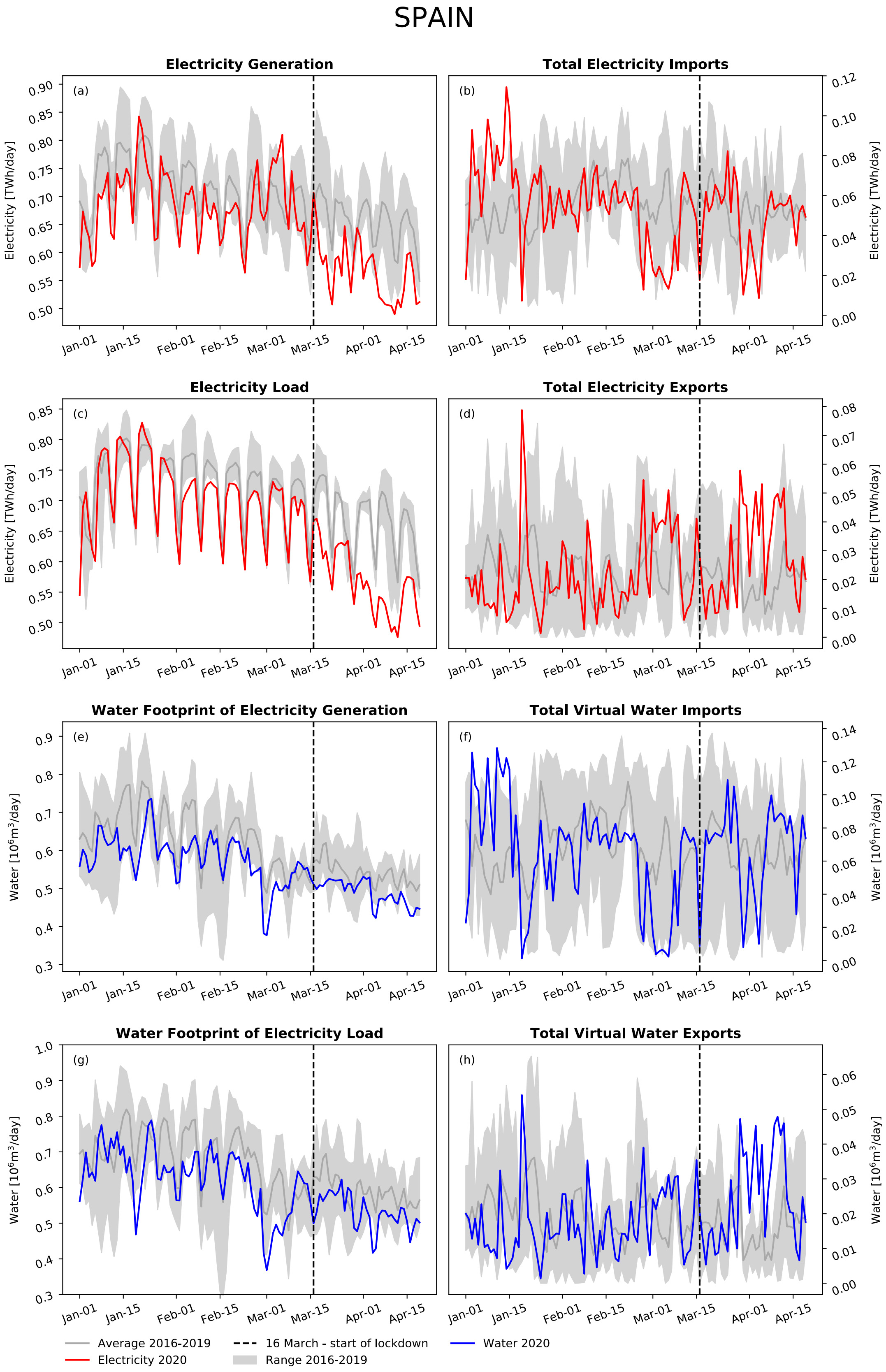


Figure 22: *For Spain, the figure shows the electricity generation (a), total electricity imports (b), electricity load (c), total electricity exports (d), water footprint of electricity generation (e), virtual water imports (f), water footprint of electricity load (g) and virtual water exports (h). Source: (Roidt et al., 2020b supplementary material).*

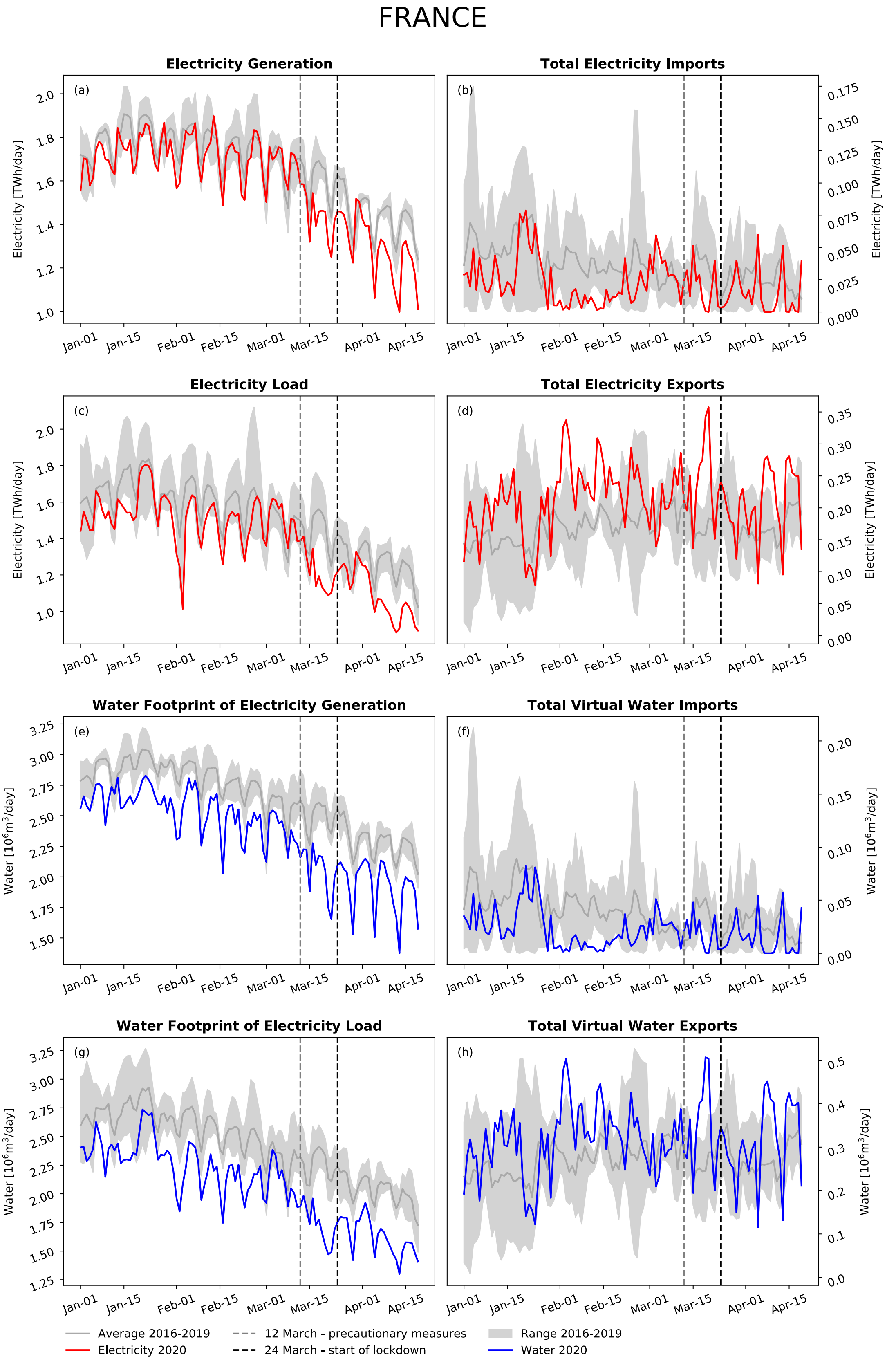


Figure 23: *For France, the figure shows the electricity generation (a), total electricity imports (b), electricity load (c), total electricity exports (d), water footprint of electricity generation (e), virtual water imports (f), water footprint of electricity load (g) and virtual water exports (h). Source: (Roidt et al., 2020b supplementary material).*

4.4 Discussion

Our results in Roidt et al. (2020b) enhanced the understanding of how the electricity-water nexus in the European electric grid responds to short-term, large-scale behavioral changes.

The analysis, however, bears some limitations regarding the methodology that must be kept in mind when discussing the results. The investigations only considered the operational phase of the power plants and did not consider the life cycle of fuel or the construction of the plants. Furthermore, the gray water footprint and water footprint of hydropower were not included. Vanham et al. (2019) studied the water footprint of the EU energy sector (electricity, heating, mobility). This cannot be directly compared to our results due to our focus on electricity. However, they provide valuable conclusions for this limitation. Specifically for electricity generation, they show the high water intensity of reservoir hydropower operation due to evaporation. This indicates that the same analysis of Roidt et al. (2020b) including hydropower would increase the water footprint, especially of countries with a higher share of reservoir hydropower. This assumption is also confirmed by Lohrmann et al. (2021), who show that hydropower accounts for over 60% of Europe´s electricity water footprint.

The sudden changes in electricity demand in Europe during the 2020 lockdown-like measures provided the opportunity to analyze how the water footprint of electricity generation is influenced by a reduced electricity generation. For virtual water trade, while in most cases the reduced electricity generation was domestic, it had effects across borders through the highly interlinked European electricity grid.

How the virtual water trade in Europe developed in the past decade was analyzed by Chini & Stillwell (2020). They report a distinct seasonality with a lower virtual water trade in the summer due to comparatively few air conditioners in Europe and high trade in the winter due to higher heating demand. The resulting annual decreasing trend through the spring season is also clearly visible (see Figure 17) in the months January – April that we analyzed in Roidt et al. (2020b). Furthermore, they identified a general increase in virtual water trade by 14% between 2010 and 2017. This increase refers to trade and not to the actual water footprint of Europe based on its electricity mix. Chini & Stillwell (2020) used static water intensity per unit of electricity between 2010 and 2017, and hence the increase in virtual water trade is not attributed to the electricity mix, but only to an increase in electricity trade within Europe. While they state in qualitative terms that a shift to renewable energies will reduce water intensity, we quantified this trend. Since we accounted for the changing electricity mix, we were able to show how the water intensity of Europe’s electricity mix has reduced in 2020 compared to the baseline average (2016 – 2019). This does not stand in contrast with the findings of Chini & Stillwell, and it can be concluded that the water footprint of Europe’s electricity generally seems to reduce due to the increase in wind and solar power, while the trade of virtual water among European countries increased.

Lohrmann et al. (2021) predict that due to the change in the electricity mix, the water footprint will reduce by more than 20% between 2015 and 2025, which is well in line with the trend in our findings from the year 2020. This however must be viewed carefully as discussed by Mapes & Larsen (2023). With a specific focus on Romania, Germany, and Spain, the authors project the electricity sector´s water use until 2050 and reveal a high sensitivity of water use with regard to the chosen technology. Especially implementing concentrated solar power (CSP) and carbon capture and storage (CCS) can increase total water consumption and withdrawal rates by an order of magnitude, should fossil thermal power plants still be in use by then.

Chini & Stillwell (2020) also analyze which countries are net importers and exporters of virtual water for 2018, showing that Germany and France are Europe’s largest net exporters of virtual water while Switzerland, Spain, and Italy import virtual water from neighboring countries. Even though we did not specifically investigate this question, our study confirms these findings. Italy is the largest net importer of virtual water among the five countries we analyzed, which is visible in Figure 19. Switzerland and Spain only import a little more than they export, as described by Chini & Stillwell (2020) and visible in Figure 20 and Figure 22. In summary, what is described by Chini & Stillwell (2020) for the year 2018 can be confirmed on a qualitative basis by our analysis at least for the months January–April of the years 2016 – 2020.

When looking at the water footprint of electricity in Europe, in Roidt et al. (2020b) and the above mentioned articles, two effects become visible.

First, is that the behavioral change during the lockdown-like measures, resulted in a reduced water footprint. This effect is driven by potentially heterogenous behaviors that cannot be exactly identified but are most likely due to reduced economic activity.

Second, there is a reduction in the water footprint of Europe’s electricity due to a shift of the electricity mix to less water-intensive technologies, i.e., wind and PV, throughout the past years. This process is a planned change in technology, mainly driven by the aim of reducing CO_2 emissions. By chance, CO_2-intensive electricity generation plants using coal, gas, or oil are relatively water-intensive, while CO_2-intensive wind and PV have a considerably smaller water footprint. Exceptions are nuclear power plants, which produce little CO_2 but have a comparatively high water footprint, and reservoir hydropower with low CO_2 and a high water footprint.

When aiming to reduce the negative impact on water resources through electricity production, actions should be taken in both fields. First, demand side interventions, i.e., through energy efficiency programs, will reduce electricity generation and related pressure on water resources. The second approach is to continue to shift to water-intensive technologies, thereby reducing the specific water footprint of each MWh of electricity produced. This topic will be picked up again in the next chapter.

5 Discussion and Outlook

MAR is an important technology in sustainable water management due to its manifold objectives and possibilities. This applies also to the context of Costa Rica. Our suitability mapping for Costa Rica showed that different parts of the country are technically suitable for further detailed feasibility studies with the objective to realize such projects.

There is no evidence in literature, that after our study in 2016 implementation of MAR in Costa Rica has increased. This aligns with the recent study of de Witt et al. (2025) describing the various barriers to implementation of MAR around the globe, but especially in developing countries. The most widely cited challenges in the study that hinder MAR from moving beyond the experimental phase are site-specific planning, research, and technical problems, operating procedures, guidelines, and monitoring as well as enabling policy frameworks and regulations (ibid.). Other challenges are public awareness, support, and participation as well as multi-disciplinarity and cooperation. Overcoming such challenges should also be the next major goal for MAR in Costa Rica.

Chapter 2.4 discussed that for major challenges of the water, energy, and food sectors, MAR can be a suitable technology, however, more than MAR is required. For example, applying a WEF-Nexus Framework to the complex challenges of the Lake Arenal Project in Costa Rica, could lead to enhancing the efficiency of the overall system in the case study. Furthermore, the WEF-Nexus contains features that could address some of the challenges in implementing MAR projects described by Witt et al. (2025).

To demonstrate how the features and aspects of integration of the WEF-Nexus could take effect in the Lake Arenal area, some preliminary defined steps for a WEF-Nexus Project are outlined in Table 14.

Table 14: *Outline of a WEF-Nexus Project at Lake Arenal in Costa Rica incl. identified features. Source: Own representation.*

Step	***Content and Applied Features and Aspects of Integration***
1	*Assembly of a team of researchers with experience in agriculture, irrigation, hydropower, hydrology, hydrogeology, electricity generation and energy systems analysis, social, cultural, economic, and policy analysis as well as experts of the Lake Arenal context i.e., experienced practitioners in irrigation, hydropower/dam operation, environmental preservation.* *WEF-Nexus features: interdisciplinarity, transdisciplinarity.*
2	*Decision on system boundary and scale of analysis i.e., a combination of watershed for hydrologic analysis, agricultural irrigated areas, electricity grid (area of affected population (where relevant).* *See Avellán et al. (2017) for our suggestions on framing boundaries.*

Step	Content and Applied Features and Aspects of Integration
	WEF-Nexus features: Consider different scales.
3	*Analysis of additional aspects of integration to consider. Examples are (i) impacts of climate change on agricultural productivity, irrigation needs, electricity demand and water availability, (ii) ecosystem demands i.e., water minimum flow, (iii) land requirements for MAR spreading basins.* *WEF-Nexus aspects of integration: Water, energy, food, ecosystems, land, climate.*
4	*Identification and quantification of the relevant biophysical interlinkages i.e., timing and quantities of water used for electricity generation (hydropower) and food production (irrigation), water availability in the reservoir.* *Hydrogeological investigations into feasibility of MAR sites for flexible use incl. interlinkages of MAR projects i.e., electricity demands for water recovery.* *WEF-Nexus features: Combine different modelling approaches, provide methods and tools for assessment.* *Examples of tools shown in Table 7.*
5	*Analysis of relevant policies, governance arrangements as well as social, political, and economic dimensions. One example is power imbalances among stakeholders and how such imbalances can be addressed to ensure successful and sustainable workshops.* *WEF-Nexus features: Consider governance, norms, institutions, and organizations, incorporating the political and social dimension, provide methods and tools for assessment, combine different modelling approaches.* *Examples of tools shown in Table 7.*
6	*Organization of workshops with relevant stakeholders i.e., experts and researchers mentioned above, representatives of farmers organizations, representatives of local communities, environmental organizations, governmental representatives (e.g., the Ministry of Energy and Environment (MINAE)), the water supply utility Instituto Costarricense de Acueductos y Alcantarillados (AyA), the electricity utility Instituto Costarricense de Electricidad (ICE), National Irrigation and Drainage Service (SENARA), the public services regulator Autoridad Reguladora de los Servicios Públicos (ARESEP).* *WEF-Nexus features: participation and inclusion of relevant stakeholders.*
7	*Identification of relevant trade-offs and potential synergies and innovative solutions at workshops of step 6 (based on the analysis in step 3 and 4).* *WEF-Nexus features: Participation and inclusion of relevant stakeholders, bring together sectors, innovation, focus on systems efficiency.*
8	*Implementation of identified solutions in governance arrangements, policy, and infrastructure projects.*
9	*Production of policy recommendations for a wider context.*

By embarking on the above-described assessment and implementation the project will apply the features of *embracing complexity* and *holism.*

Such projects must carefully be designed, planned, and financed. Especially analyzing various interlinkages across sectors and bringing together a diverse group of stakeholders will need preparation, time, and flexibility. When designing a WEF-Nexus Assessment the above steps will need to be formulated in more detail, and this chapter can only give an initial overview based on what was conceptually described for a WEF-Nexus Framework.

To continue a conceptual description of a WEF-Nexus Framework it is also important to produce a refined and detailed understanding of the features and integration in a WEF-Nexus Framework. What exactly is meant by considering governance in the WEF-Nexus? How does interdisciplinarity and transdisciplinarity materialize? These and many more questions on the WEF-Nexus features must be answered. Thus, understanding of the features and integration in a WEF-Nexus Framework must now be understood in depth. This dissertation revealed *that* such features are part of the WEF-Nexus; further studies should reveal *how* these features contribute to the WEF-Nexus, guiding us one step closer to a full description of a WEF-Nexus Framework. A suggested methodology for a future literature review is to scan the WEF-Nexus literature not for conceptual articles, but for articles that focus on that very feature. An example is that from the 2,398 WEF-Nexus articles of research phase 2, a total of 11 articles tackle the issue of *participation of stakeholders*, or 22 articles focus specifically on the feature of *governance*. Due to their narrow focus, such articles were not considered as conceptual articles but are relevant in a detailed study on each of the features.

A similarly detailed investigation is now necessary for the aspects and interlinkages to be integrated. By using the category of integration concept, a literature review can identify the linkages between the aspects to be integrated from biophysical to legal. Such a study will help to reveal which interlinkages are the most relevant to consider in a WEF-Nexus and how they may be tailored to each context and model.

A conceptual contribution on the scales and the boundary for nexus assessments is needed. While in Avellán et al. (2017) we provide some thinking towards this goal for the WSW-Nexus, a structured analysis is needed for a WEF-Nexus Framework.

With regard to the contribution towards a definition of a WEF-Nexus, some initial conceptual clarity is provided in Part B. This, however, needs further analysis. To precisely describe the WEF-Nexus and to ensure that researchers from a variety of disciplines and practitioners can communicate in precise terms, the semantics and ontology of the Nexus should be described. This can build on – yet will need to be more comprehensive than – the provisions in this dissertation, the glossary provided in Lucca et al.(2025), the typology by Jones-Crank (2025) or the ontology provided by Endo et al. (2018).

The continued development of the WEF-Nexus from a conceptual point of view is fueled by countless examples of how the nexus between water, energy, and food is analyzed. One example is the analysis of the calculation of the water footprint in the European electricity grid. This calculation method can support the quantification of one of many WEF-Nexus interlinkages. In the following it is described how the computation of interlinkages presented in Part C at the sub-annual scale could be developed into a tool within the context of a WEF-Nexus Framework.

For water resources management, the scale of the watershed matters most. To aggregate electricity production and related water footprint, the data must be available at the level of the individual power plant. This is already partly the case and has been published by ENTSO-E. The quality of the data is, however, not sufficient. In a conference presentation in 2020 with data from 2018, we concluded that from the >7,000 power plants in Europe, only a fraction of data is available, mainly because many power plants do not provide data at all (Roidt et al., 2020a). A recalculation with data between 2015 and 2024 shows a high percentage of missing data at the unit level between 77% and 92%. A reliable water footprint at the power plant level with aggregation to the watershed level, therefore, does not seem realistic at the moment. However, the reporting infrastructure and ENTSO-E's aim to reliably report at the power plant level is already in place (ENTSO-E, 2019; European Union, 2013). Hence, this topic should be monitored to seize the opportunity when data reliability improves.

What is available, however, are aggregated data at the country scale. ENTSO-E gathers electricity data aggregated by production type as well as electricity trade between countries in hourly or sub-hourly resolution and is required to publish them “no later than one hour after the operational period” (European Union, 2013, p. L163/9). Using the methodology described in Chapter 4.2 and the specific water consumption per production type described in Chapter 4.1, the water footprint of Europe’s electricity mix, and virtual water trade can be calculated and monitored close to real time.

This simple calculation can enable the following:

Increase awareness: Publishing the water footprint of electricity will help to increase awareness about the water consumption of electricity and how it can be reduced. This can be done through publishing statistics of past periods in articles, e.g., from past years, etc. Furthermore, (near) real-time observation of the water footprint can be monitored online by interested stakeholders (with electricitymaps.com, this is already the case for the CO_2 footprint and will be described below). Users of smart homes could monitor their electricity consumption and related water footprint. Several smart home appliances already report on current CO_2 intensity of electricity (Home Assistant, Schneider, Smart Things (Electricity Maps, 2025a). The same could be implemented for the water footprint.

In many countries i.e., in Germany a high awareness exists towards water conservation through classic approaches such as using water saving appliances, water saving showerheads or reducing unnecessary running of the water tab. Making available a monitoring tool to track the water footprint of electricity will help to increase the understanding of the indirect influence on water conservation and how, e.g., shifting to a renewable electricity provider can improve water conservation.

Incentive for private actors to reduce water footprint: Companies in Europe increasingly need to report on their sustainability performance. Two examples that are becoming more relevant are the EU Corporate Sustainability Reporting Directive (CSRD) (European Union, 2022) and ratings on environmental, social, and governance aspects of companies (ESG ratings).

The CSRD, implemented by the EU in 2023, aims to standardize and improve reporting on sustainability indicators of mainly medium and large companies in the EU market (Operato et al., 2025). The directive includes five reporting standards where the European Sustainability Reporting Standard (ESRS) No. 3 solely focuses on water and marine resources. This includes several indicators on water use, water use efficiency of company’s production or service (European Union, 2023).

Providers of financial data and credit ratings, such as Bloomberg, FTSE Russell, MSCI, S&P Global, etc., are now often also providing ESG ratings (Mazzacurati, 2021). This includes the theme of water resources as well. MSCI, for example, specifically includes the water footprint of a company in its ESG ratings methodology on water stress (MSCI ESG Research LLC, 2024). Sustainalytics, a global leader in ESG ratings, also suggests that water metrics at the company or country level are reviewed (Karoui & Zerter, 2022). Sustainable investing has seen significant growth in recent years (Mazzacurati, 2021). Therefore, ESG ratings and the underlying information including information on water risk and water security are becoming increasingly important to companies worldwide.

For these requirements, understanding the water footprint that a company has through electricity consumption will improve its reporting, especially since the information can be easily and automatically made available. Furthermore, this metric will provide companies with the possibility to improve the water footprint, i.e., if a company has the possibility to flexibly use electricity at low water-intensive periods of production. Another example is that a shift to using solar and wind power will not only improve a company’s CO_2 impact but, at the same time, its water footprint.

Providing an indicator of the electricity water footprint will therefore improve reporting and provide an incentive to reduce the water footprint by companies with a high electricity demand.

This effort might even go beyond the company scale to entire governments that may want to address water conservation in the electricity sector. This is addressed by Chini & Stillwell arguing that “[c]ountries concerned about their total water footprint as part of sustainability efforts might choose to import electricity from countries other than Germany due to their high water intensity” (Chini & Stillwell, 2020, p. 5).

Incentives to reduce water intensity through electricity pricing: If governments aim to reduce the water footprint of electricity, the cost of consumed water could be included in electricity pricing. Similar to a tax on CO_2, a tax on the water footprint can develop a steering effect towards less water-intensive electricity production. Here, however, further research is necessary to clarify the economic effects of such a tax, the practicability and possible current fees of water withdrawal and consumption at the power plant level.

The enterprise *electricity maps* are already offering such a tool for the CO_2 intensity of the global electricity mix. Published online, the tool shows the near-real-time CO_2 footprint of a country’s electricity mix and how this is traded across borders. The overall aim is “to provide a free, open-source, and transparent visualization of the carbon intensity of electricity consumption around the world” (Corradi, 2025 n.p.).

An example for Europe is shown in Figure 24, where Germany has an overall emission of 316 g CO_{2eq}/kWh on 4 May at 21:00 with a share of 62% renewable energies. The remaining power was produced from coal and gas at that time. Furthermore, the current imports mainly from Switzerland, Denmark, France are visible and numerically available.

As paid service electricity maps publishes forecasts on prices, electricity mix and CO_2 intensity. Among others, the aim is to provide companies with the information to reduce their CO_2 footprint by buying CO_2 extensive electricity if flexible electricity use is possible i.e., in data centers (Electricity Maps, 2025b).

Data are fetched from several publicly available sources, including ENTSO-E for Europe (Corradi, 2025), hence building on the same data used in Roidt et al. (2020b).

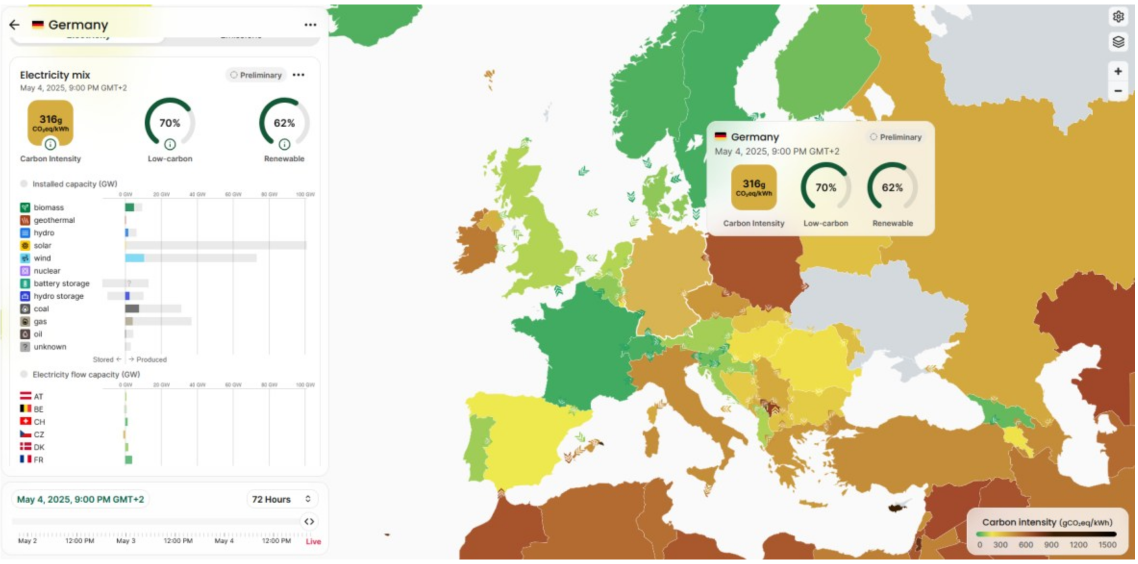


Figure 24: *Screenshot from electricity maps showing Germany on 4 May at 21:00 with an overall emission of 316 g* CO_2*eq/kWh and a share of renewable energies of 62%. Source: (Electricity Maps, 2025b).*

With electricity maps a basis for the above-described monitoring tool is already laid. By integrating the water intensity per electricity production type, electricity maps could be expanded by *virtual water maps*. Therefore, the water footprint of electricity could be tracked at a high timely resolution.

Even though highly disaggregated data at the power plant level are not reliably available, another piece in the puzzle of a WEF-Nexus Framework can be a monitoring tool that provides up to date information on the water footprint of electricity production and trade.

6 Conclusion

This dissertation provides considerations of MAR, conceptual analyses and computations of water-electricity interlinkages within the context of the WEF-Nexus.

It first provides considerations of MAR as a water resources management tool within the context of the WEF-Nexus. Using the example of Costa Rica, a suitability map of MAR-type spreading methods was produced based on different input parameters. Based on the analysis roughly 30% of the country is suitable with either very high or high potential for MAR-type spreading methods. MAR can serve as an import tool to buffer water for domestic use from the rainy season to the dry season. Based on two examples in Costa Rica it was discussed that more tools in addition to MAR are needed to solve combined challenges at the nexus of the water, energy, and food sectors where not only infrastructure investments are needed but governance issues must be solved and policy coherence ensured. An integrated approach aiming to tackle such challenges is the WEF-Nexus with which MAR can be used as one of several technologies.

Second, the dissertation contributes to a better understanding of what constitutes the WEF-Nexus. It enhances the understanding of where we stand in defining a WEF-Nexus Framework. First it provides information on earlier Integrated Management Approaches and how they have paved the way towards the WEF-Nexus. Second it presents an overview of 32 different Nexus Frameworks, roughly a dozen main features of the WEF-Nexus and up to 21 different aspects that may be integrated within the WEF-Nexus. However, in defining a WEF-Nexus Framework, more research is needed and ongoing (see e.g., most recent conceptual articles of 2025 in Table 3 or WEF(E) projects mentioned in Chapter 1). Chapter 5 provides ideas on how the findings of this dissertation can be enriched with details on features and integration aspects. Conceptually defining a WEF-Nexus Framework must not remain an academic exercise but should culminate within a well described and delineated concept. However, due to its application in many contexts, a WEF-Nexus Framework cannot result in a blueprint where every interlinkage is defined, models are pre-selected or participation workshops conceptualized; yet it must provide a methodology on e.g., which aspects to integrate, how to apply its features and how to identify relevant interlinkages among many more aspects. Within the past decade a lot of knowledge was produced within the context of the WEF-Nexus. Therefore, the vision of a Standard Textbook on the WEF-Nexus Framework could be realized in the next decade. This will support researchers, practitioners, policymakers, and funding institutions in understanding whether in a given context a WEF-Nexus Framework is applied including all defined steps and features or if just any activity, analysis or investment along the lines of a nexus between water, food, and energy is carried out. With a WEF-Nexus Framework many tools and computation methodologies and models will be used and needed.

In the third part such a computation of interlinkages is provided and a tool for a WEF-Nexus Framework is outlined in Chapter 5. The computations we presented in Roidt et al. (2020b) show the changes of the water footprint of electricity generation in Europe as the COVID-19 pandemic hit the continent. We showed a reduced water footprint due to three phenomena: a medium-term shift in the electricity mix in the years before the pandemic towards less water intensive electricity generation, a short-term shift to less water intensive electricity generation during the lockdown-like measures as well as a reduction in electricity generation during the lockdown-like measures. We further show the changes in virtual water among five European countries and how imports and exports shifted. Thereby we contributed to an increased understanding of the water-electricity nexus of sub-annual water footprints and virtual water trade in a highly dynamic period such as the COVID-19 pandemic. Based on the methodology of this analysis, the data availability was analyzed with the aim of outlining a tool that monitors Europe's water footprint and virtual water trade in near real time. Such a tool could be used in a WEF-Nexus Framework to increase awareness about water use in electricity generation, incentivize private actors to decrease their water footprint and to create incentives in the electricity market to reduce water intensity in electricity generation through pricing mechanisms.

The scholarly discourse on the nexus between water, energy, food, and other related sectors is ongoing. This dissertation contributes to this debate to advance the WEF-Nexus conceptually and practically so that it can better tackle challenges at the interface of water, energy, and food, thereby supporting sustainable development in Costa Rica, Europe, and beyond.

7 List of References

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8 Annex

This annex includes publications relevant for this dissertation

8.1 Publication 1

Application of a GIS Multi-Criteria Decision Analysis for the Identification of Intrinsic Suitable Sites in Costa Rica for the Application of Managed Aquifer Recharge (MAR) through Spreading Methods

J. P. Bonilla Valverde, C. Blank, **M. Roidt**, L. Schneider, C. Stefan

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Article

Application of a GIS Multi-Criteria Decision Analysis for the Identification of Intrinsic Suitable Sites in Costa Rica for the Application of Managed Aquifer Recharge (MAR) through Spreading Methods

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Abstract: Costa Rica's annual mean precipitation is above 3300 mm, but this precipitation is not evenly distributed in time or space, producing clear differentiated wet and dry seasons in most of the country. Droughts are also common phenomena which greatly affect the availability of water resources. Managed aquifer recharge (MAR) schemes are being taken into consideration to enhance the underground water storage capacity of the country. The present study constitutes the first assessment for the identification of suitable sites for the implementation of MAR technology spreading methods (SM) in Costa Rica. The suitable sites are identified by means of a geographic information system multi-criteria decision analysis (GIS-MCDA) based on four criteria: hydrogeological aptitude, terrain slope, top soil texture and drainage network density. Four steps are performed in order to identify these sites: problem definition, screening for suitable areas, suitability mapping, and sensitivity analysis. The suitability map was divided in two zones after the screening: suitable and unsuitable, the first zone was further divided in five classes according to the weighted linear combination (WLC) ranking. The results indicate that 61% of the country is suitable for conducting SM. This map is a tool for future implementation of MAR techniques in the country.

Keywords: Costa Rica; managed aquifer recharge; spreading methods; geographic information system multi-criteria decision analysis; suitability mapping; multi-influence factor

1. Introduction

Costa Rica is located in the Central America isthmus in the northern hemisphere tropical zone, between the Pacific Ocean and the Caribbean Sea with a total surface area of 51,100 km^2 [1]. The country's climate is tropical, dominated by trade winds and its mountain systems [2]. This leads to a mean annual rainfall of over 3300 mm—of which two-thirds become runoff [3]. This amount of water is not equally distributed, neither in time nor space. In the Pacific and Central regions there is a marked difference between the wet and dry season, the latter with almost no rain during four months of the year [2].

The country presents a complex geology [4] and topography [5]. The mountain ranges are composed mainly of volcanic formations, while the Northern and Tortuguero lowlands and the coastal areas are mostly alluvial depositions from eroded material transported from the elevated steep mountain areas [4]. The spatial distribution of these features is shown in Figure 1 while a detailed description of the country's geological formations is given elsewhere [4,6,7].

Topographically, the country presents lowland plains, valleys, plateaus, and mountains over 3000 m in height; that favors the development of different climatic regions. Three mountain ranges (Guanacaste, Central, and Talamanca cordilleras) cross the country from northwest to southeast which is the principal orographic feature [5]. The river discharge variations are driven by the seasonal rainfall differences, especially in the Pacific watersheds, where the relatively short distances from the Guanacaste and Aguacate cordilleras to the oceans limit the length of river system and triggers the quick response to rain events [4].

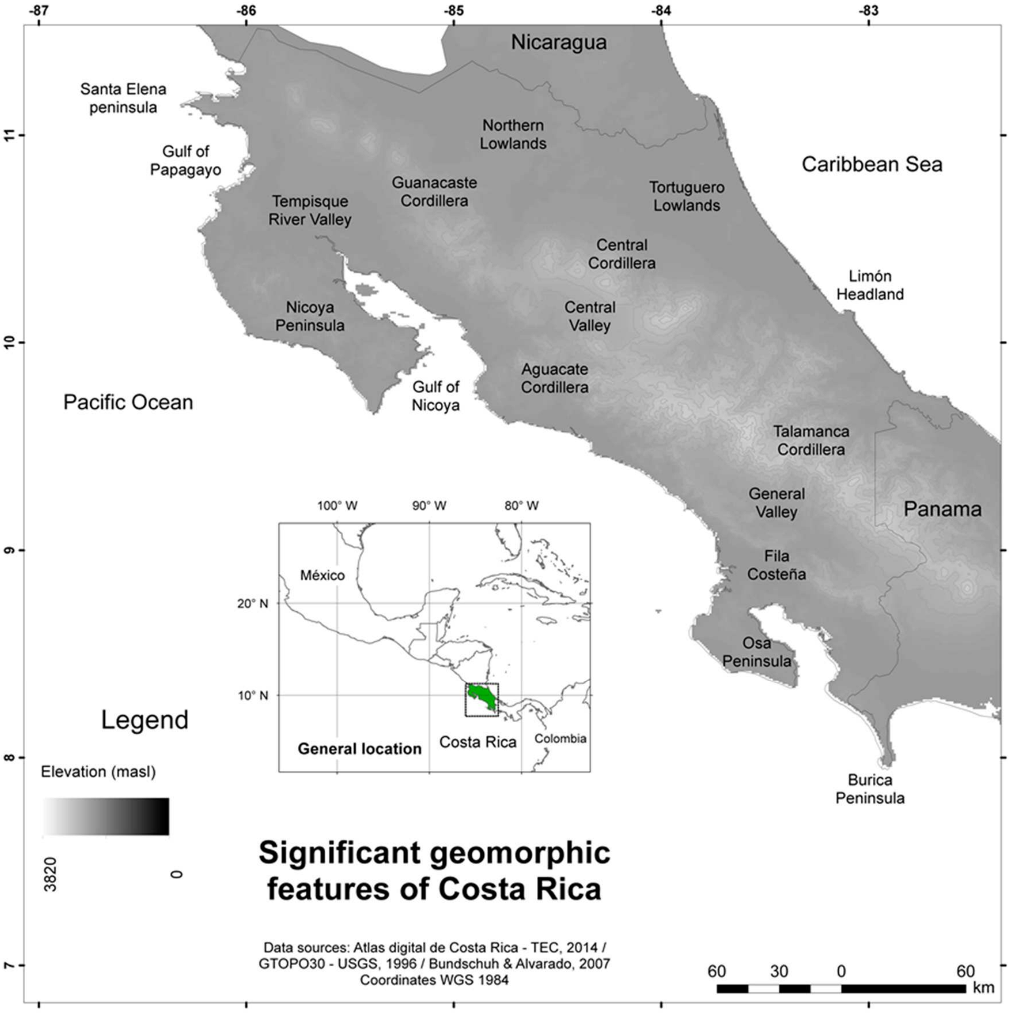

Figure 1. Main geomorphic features of Costa Rica based on Bundschuh and Alvarado [4] with base digital elevation model by the USGS [8].

The abundance of water in the wet season, the fast runoff into the oceans, and the touristic high season coinciding in time with the dry season, make managed aquifer recharge (MAR) a viable approach to overcome the drought issue, especially for the water supply systems in Costa Rica. According to Dillon [9], MAR is defined as the intentional banking and treatment of water in aquifers; moreover, it may also be applied for the recovery of falling water levels in the aquifer as well as preventing saline water intrusion or land subsidence [9]. MAR methodologies are classified in five main categories: (a) spreading methods; (b) induced bank infiltration; (c) well, shaft, and borehole recharge; (d) in-channel modifications; and (e) rainwater and run-off harvesting; these are subdivided in specific MAR types [10,11]. This study aims to identify and rank the suitable sites for applying the

MAR category spreading methods (SM), which aim to recharge an unconfined aquifer at or near the ground surface by infiltration through permeable materials at the surface [10].

The main objective of this work is to identify the areas in Costa Rica that present the best intrinsic conditions (environmental and physical criteria) to conduct further research on MAR—rather than sorting out the unsuitable sites for it. Other factors (land use, existing infrastructure, water sources, and economics, among others) are not taken into account as these factors can change with time, while the intrinsic factors tend to be more or less constant. Nevertheless, for the implementation of specific MAR schemes, socioeconomic variables should be analyzed.

This study uses the methodology proposed by Rahman et al. [12]. The MAR suitability map is calculated and displayed at 1:500,000 scale for the whole country. This map is a first level screening tool that serves as a basis for decision making where detailed investigations should be carried out. The applied approach can easily be supplemented with additional data.

2. Materials and Methods

2.1. Geographic Information System Multi-Criteria Decision Analysis (GIS-MCDA)

GIS-MCDA is defined as a collection of methods and tools for transforming and combining geographical data and preferences (value judgments) to obtain information for decision making [13,14]. GIS offers the capabilities to automate, manage, and analyze a variety of spatial data—while MCDA comprises a wide range of methodologies, techniques, and procedures that guide the decision making process [13]. GIS-MCDA is used to rank the available areas based on decision rules that define how the standardized criteria are integrated. For a detailed description of GIS-MCDA and the concepts it involves see [13,14].

According to Rahman et al. [12] the ranking of potential MAR sites may be performed more comprehensively and at a lower cost using a MCDA integrated into GIS. GIS-MCDA for the identification of MAR suitable sites has been applied to entire countries such as Australia [15] and Spain [16], as well as in many regions of the world, for example in India [17–23], Iran [24–27], Jordan [28,29], Portugal [12,30], Tunisia [31,32], and the United States [33,34]. The general process for MAR site suitability analysis proposed in [12] is: problem definition, screening of feasible areas, suitability mapping—including the classification of thematic layers or criteria, standardization, weighting of the criteria and layers overlaying—and sensitivity analysis.

2.1.1. Problem Definition

The recognition of the decision problem is the first step in all decision processes (as GIS-MCDA for MAR) [13]. The objective of site selection is to identify the best site for a given activity which is done by the ranking the basic analysis units in which the study area is subdivided [14]. Suitable site selection for proper MAR technologies is one of the primary requirements for a successful MAR implementation [12].

2.1.2. Screening Suitable Areas

Areas that are not feasible for MAR (or not available) are screened out by means of Boolean logic algebra [12]. Boolean logic involves the logical combination of binary maps (only zero or one values are assigned to each unit area) by "AND" and "OR" operators [25]. In Boolean logic, an area is either accepted or rejected based on a given threshold value [35]. The criterion value that satisfy the threshold are assigned with a value of 1, otherwise 0 is assigned; if all the criteria for a specific location contain a value of 1 the resulting map will contain a value of 1 for this location, if only one on the criterion contains a value of 0, the location will also be assign a 0 [12].

2.1.3. Suitability Mapping

Suitability mapping is done to estimate the ability of the study area to support a specific use [36] defined in the problem definition. The suitability map is built to identify the areas with high infiltration rates as well as the terrains where the conditions are favorable for the construction of the infrastructure necessary to enhance the recharge process. This is the most important step in GIS-MCDA [12]. The Weighted Linear Combination (WLC) method is the decision rule applied in this work to overlay the criteria to identify the suitable site. A short description of the suitability mapping components and concepts are listed below:

- Decision rule—WLC

The decision rule is the fundamental part of the suitability mapping and therefore GIS-MCDA dictates how to rank the alternatives [13]. WLC is one of the most popular decision rules [12–14,37]. It consists of the linear aggregation of the product of criterion weights and values [14]. A comprehensive approach to the critical elements of the WLC is presented in [37], these are weight assignment to the criteria and the procedure to commensurate them (normalizing the criteria).

- Criteria

The environmental factors that govern the groundwater recharge, occurrence, and movement in a region depend upon geology, geomorphology, land cover, and natural precipitation [38]. The term criterion involves both the concepts of objectives and attributes [13,14,37]. A criterion refers to the desire state of geographical system (objective) and any property that distinguishes it (attribute) [13]. According to Malczewski [13] every criterion has to be compressive and measurable. Furthermore, it is recommended that the criteria be complete, operational, decomposable, non-redundant, and minimal.

- Standardization

A common scale is needed to describe the relative level of the criteria. This is achieved by the transformation of the criterion to comparable units; ergo, standardization [13]. Step-wise and linear functions are the two standardization methods. In accordance with Rahman et al. [12] step-wise functions are used to standardized aggregation criterion.

- Weight assignment—multi-influencing factor

The assignment of different weight for the integration of the criteria is necessary as not all them have the same degree of influence [39]. Weight assignment is one of the critical elements in the WLC [37]. In this work, the multi-influencing factor (MIF) is used for the explanation and assignment of the weight. The MIF method is described in [39,40] where the relationships between the criteria are established in a graphical way.

The estimation of the weights between the criteria is done based on the effect that they have among each other and the objective; the weighting for each criterion depends upon the interrelations between each—it can have either a major or minor effect [39]. According to Shaban et al. [39] a major effect is given 1 point while the minor effect is given 1/2 of a point. From the cumulative score of both major and minor effects for each criterion the relative rate is calculated which is further used to compute the weight of each influencing criterion [40].

2.1.4. Sensitivity Analysis

Sensitivity analysis in MCDA is defined by Malczewski and Rinner [14] as a set of methods for assessing uncertainty in the multi-criteria model output and the importance of the model input factors as the criterion values and weights. These factors (criterion values and criterion weights) are the main sources of uncertainty in the GIS-MCDA [14]. Performing a sensitivity analysis makes a more robust decision rule for the selection of site suitability [41].

Methods and instructions for the sensitivity analysis are available in [12–14,19,35,41]. These include "one-at-a-time" methods and "variance-methods" [14]. Sensitivity analysis has been carried out to demonstrate the effect of changes of the criterion weights on the spatial distribution the suitability mapping in [12,35,41]. A sensitivity analysis completed by changing the criterion values is given in [19]. As in [35], in this study the sensitivity analysis is done on the criterion weights; ergo the MIF method. The criterion weight sensitivity analysis is done by changing the weight by a small amount and evaluating its effect, in this case; the amount of the change was defined by adding or erasing relationships between the criteria; thus, altering the decision rule by small variations in the MIF method.

2.2. Criteria Used in the GIS-MCDA

Four spatial parameters in the form of thematic layers are chosen as criteria to identify the suitable sites for applying SM in Costa Rica. These are: hydrogeological aptitude, terrain slope, soil texture, and drainage network density. The screening of suitable areas is done by the integration of two of these thematic layers by means of a Boolean logic: terrain slope and soil texture. The hydrogeological aptitude and drainage network density are not considered restrictive criteria; hence, they are not used for the screening map but are used for the suitability analysis. Each criterion is explained in the next sections.

2.2.1. Hydrogeological Aptitude

The aquifer type, extent, water-holding capacity, and depth are relevant information for the site selection, as well as the distance to a water source and to the potential users [15]. Astorga and Arias [42] defined hydrogeological aptitude as the characteristic of a geological rock formation that expresses the potential to have an unconfined aquifer that may be used for various human activities. The hydrogeological aptitude for Costa Rica is based on the identified geological formations in the Costa Rica Geological Map in a 1:500,000 scale [7] and it takes into account the rock formation attributes—lithology, extension, and general physical characteristics. The geological formations are classified as: with potential or without potential [42].

The objective of the work by Astorga and Arias [42] was to identify which areas of the country have a higher vulnerability of contamination of the unconfined aquifers from anthropic activities, and not to represent the actual aquifers that exist in Costa Rica, ergo, it represents the rock formations that have the potential to hold an unconfined aquifer. A volcanic or sedimentary formation without potential does not limit the existence of aquifers by the fracture system of each formation [42]. The most important aquifers for public water supply of the Costa Rica exist in this type of formation [1].

The first category (areas with potential), is further divided in three sub-categories: areas with high potential, moderate potential and low potential. Figure 2 shows the hydrogeological aptitude defined in [42]. In Figure 2, parts of the Santa Elena, Nicoya and Osa peninsulas are classified as without potential [42] which corresponds to gabbro and ocean floor rocks mafic and ultramafic igneous complexes [4,7]. Astorga and Arias [42] also identified the mountain range between the Guanacaste and Central cordilleras (dissected remnants of stratovolcanoes—locally known as Monteverde Formation [7]) and the granite intrusive in Talamanca [7] as without potential.

Regarding the areas with hydrogeological potential, Astorga and Arias [42] assigned a low potential to the andesitic lava flows in the Northern Lowlands [7] as well as most of southern Costa Rica which correspond more significantly to the Talamanca extrusive rocks, the Caribbean interbedded limestones, and Central and Fila Costeña dendritic series among others [7]. Ignimbrites to the east of the Guanacaste cordillera and sandstone, marine sands, conglomerates, and turbidite beds in the south of the Nicoya Peninsula (Nicoya complex), the Caribbean and the Osa and Burica peninsulas identified in [4,7] are classified as with moderate potential in [42]. The stratovolcanoes of the Central cordillera and the quaternary deposits in the Northern and Tortuguero lowlands; the Tempisque and General valleys; and coastal Pacific and Caribbean shores are classified with high potential [42].

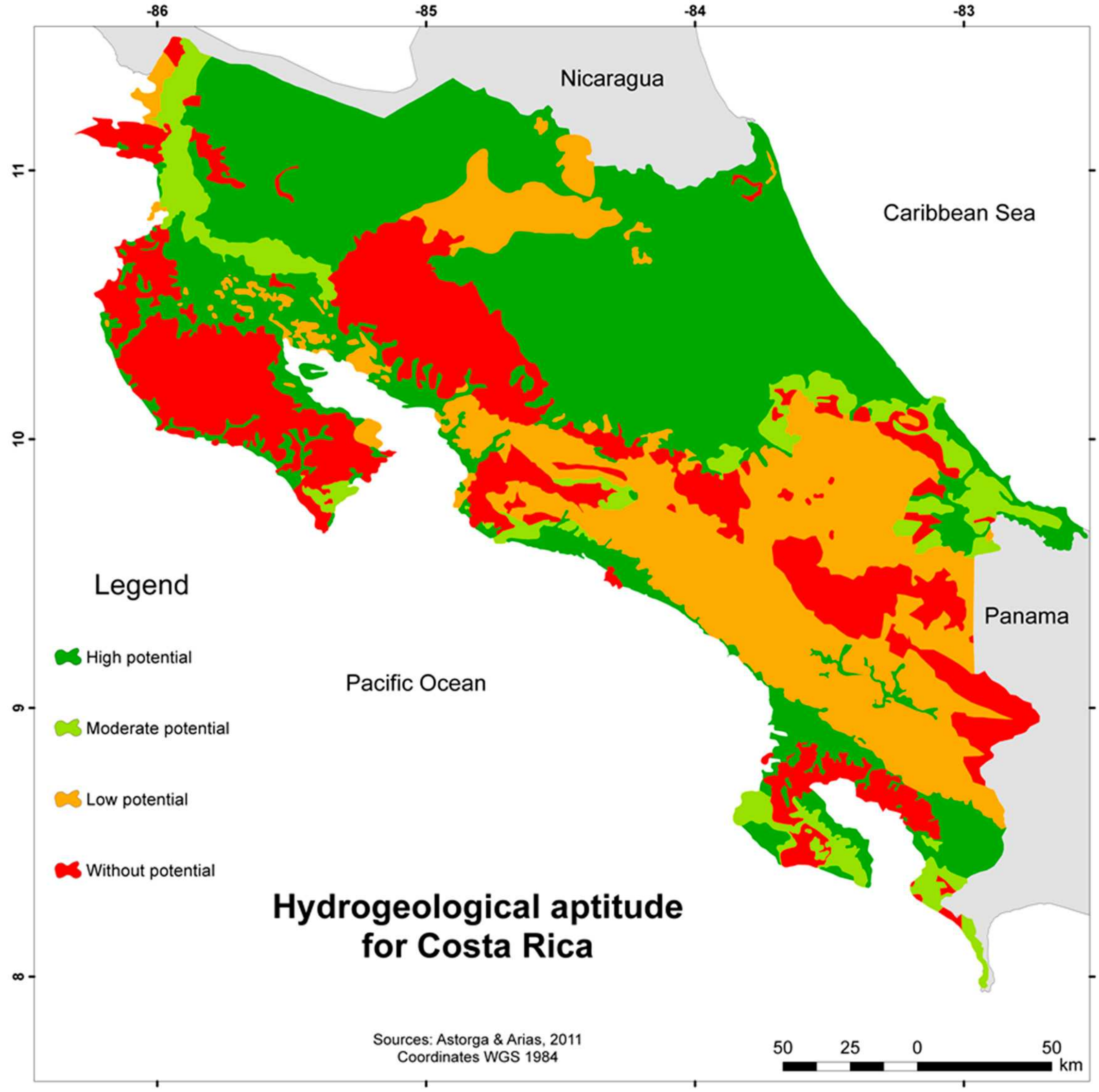

Figure 2. Hydrogeological aptitude for Costa Rica based on Astorga and Arias [42].

2.2.2. Terrain Slope

Mainly referred as slope in previous works, the terrain slope is one of the main criteria that control natural recharge in a basin water balance; it is considered the most important attribute of terrain topography governing groundwater infiltration [12]. The slope describes the inclination of a direct line between two landmarks and their respective heights. It is suggested [43] that under steady conditions with a rainfall rate much greater than the saturated hydraulic conductivity, the subsurface flow decreases with increasing slope angle. Thus, slope has a substantial influence on infiltration rates. Furthermore, water velocity is directly related to the terrain slope.

On steep slopes, runoff is more erosive, thus easily removing and transporting detached sediments down the slope [25]. Consequently, soil instability can occur. This could risk safety of an infiltration pond [32]. Moreover, steeper slopes do not permit the implementation of infiltration basins. Therefore, gentle slopes (<5%) increase infiltration rates and are suitable for aquifer recharge [12], while high slopes have poor groundwater infiltration conditions, thus are unsuitable for SM [19]. The slope classification for the country presented in Figure 3 is based on the Digital Elevation Model (DEM) with a 30 meter pixel size published in the Costa Rica Digital Atlas by the Tecnológico de Costa Rica (TEC) [44].

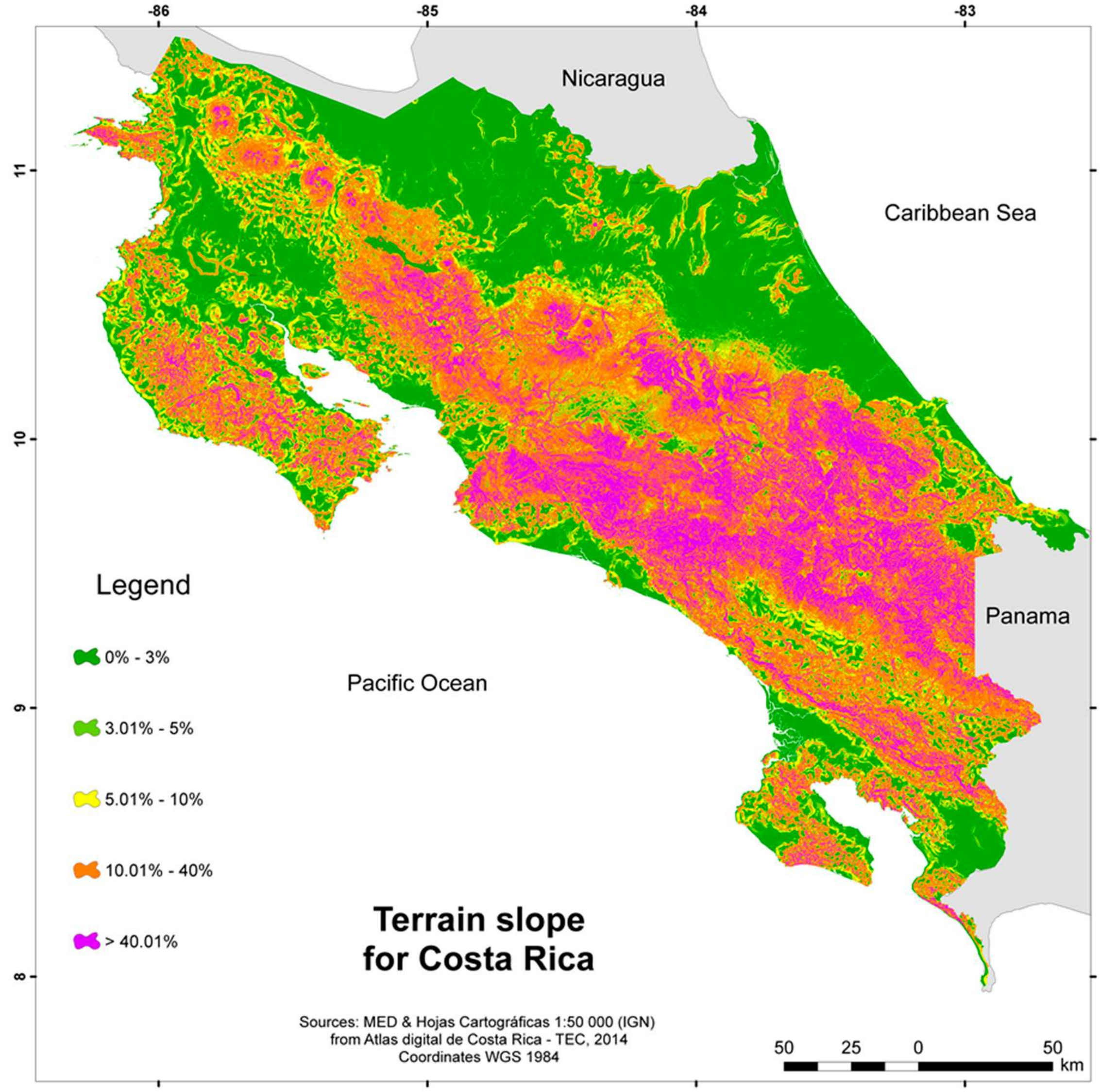

Figure 3. Terrain slope for Costa Rica based on the DEM by the TEC [44].

2.2.3. Top Soil Texture

Soils texture was identified as the main influence parameter of the soil capacity to support infiltration of water into the subsurface [20,22]. Coarse-texture soils (such as sands) have large pores that facilitate water drainage in contrary to the fine pores in clay that retard drainage [45]. The higher the clay content in the soil, the lower the permeability (thus inhibiting the infiltration). Therefore, a low clay fraction (<10%) is favorable for infiltration [32]. The soil data collected by the Ministerio de Agricultura y Ganaderia of Costa Rica (MAG) at 1:500,000 scale digitalized by TEC [44] is shown in Figure 4 with the respective soil texture classes.

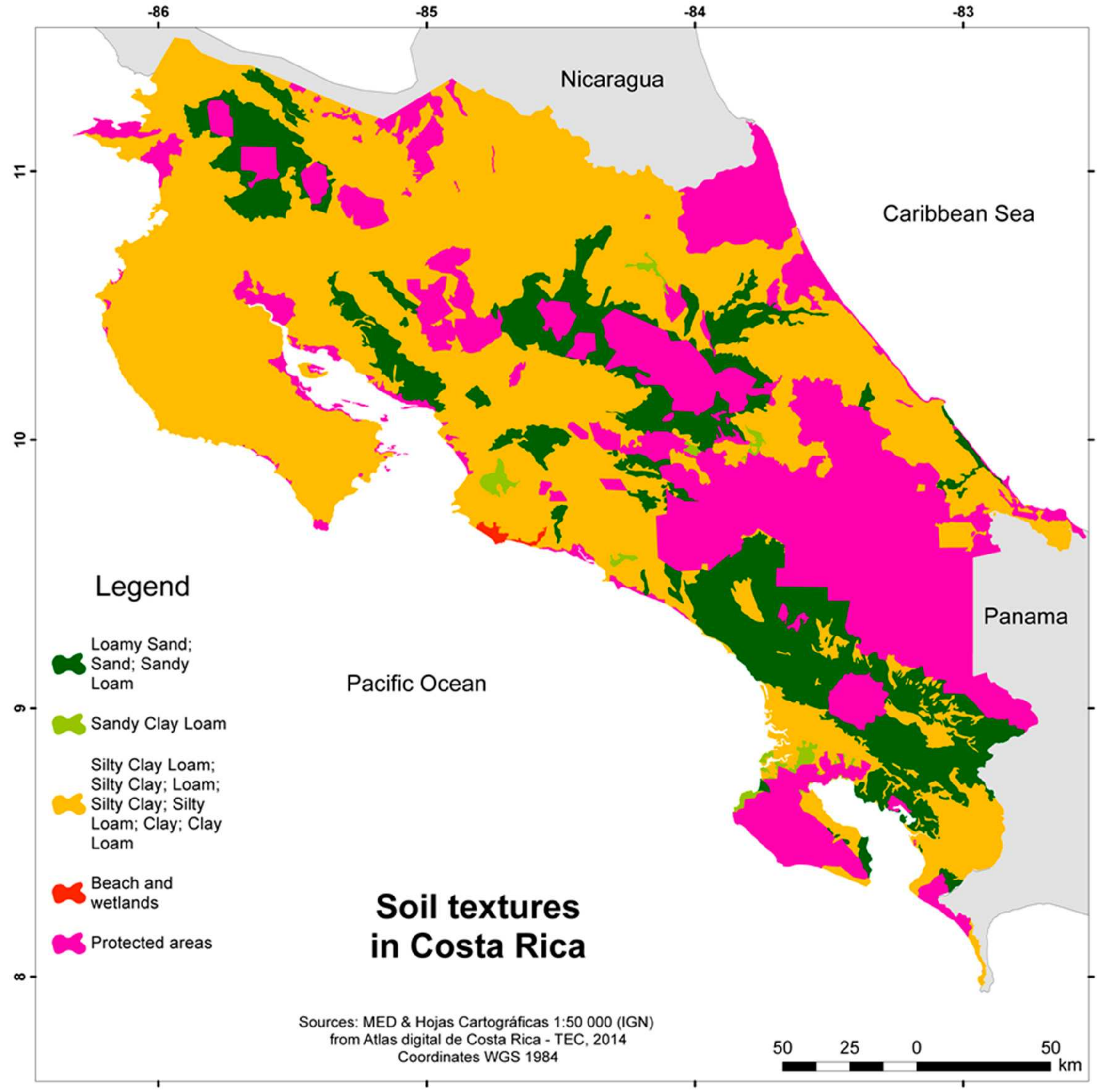

Figure 4. Soil texture based on the soil data collected by the Ministry of Agriculture of Costa Rica (MAG, in Spanish) digitalized by TEC [44].

2.2.4. Drainage Network Density

According to Shaban et al. [39], one of the most important morphometric properties of a drainage system is the drainage density. Drainage network density or drainage density is an indicator for the natural infiltration of a terrain—a higher drainage network density reflects a higher runoff, hence less infiltration; or as stated in [39] the denser the drainage network, the lower the recharge rate. Infiltration depends upon surface runoff and permeability [17]; less permeable soil formation allows less infiltration whereas permeable ground leads to a low drainage density. Thus, areas with low drainage densities are considered favorable for MAR. Drainage network density is calculated from the division of the length of all the rivers in the basin divided by the area of the basin [45].

The river network was obtained from the cartography maps (1:50,000) compiled by the Costa Rica National Geographic Institute. Small inconsistencies—such as hydraulic structures, channels, aqueducts, and river banks in the original maps were removed before further processing the river networks, in order to obtain rivers consisting of only one line per river. The drainage network thematic layer is presented in Figure 5.

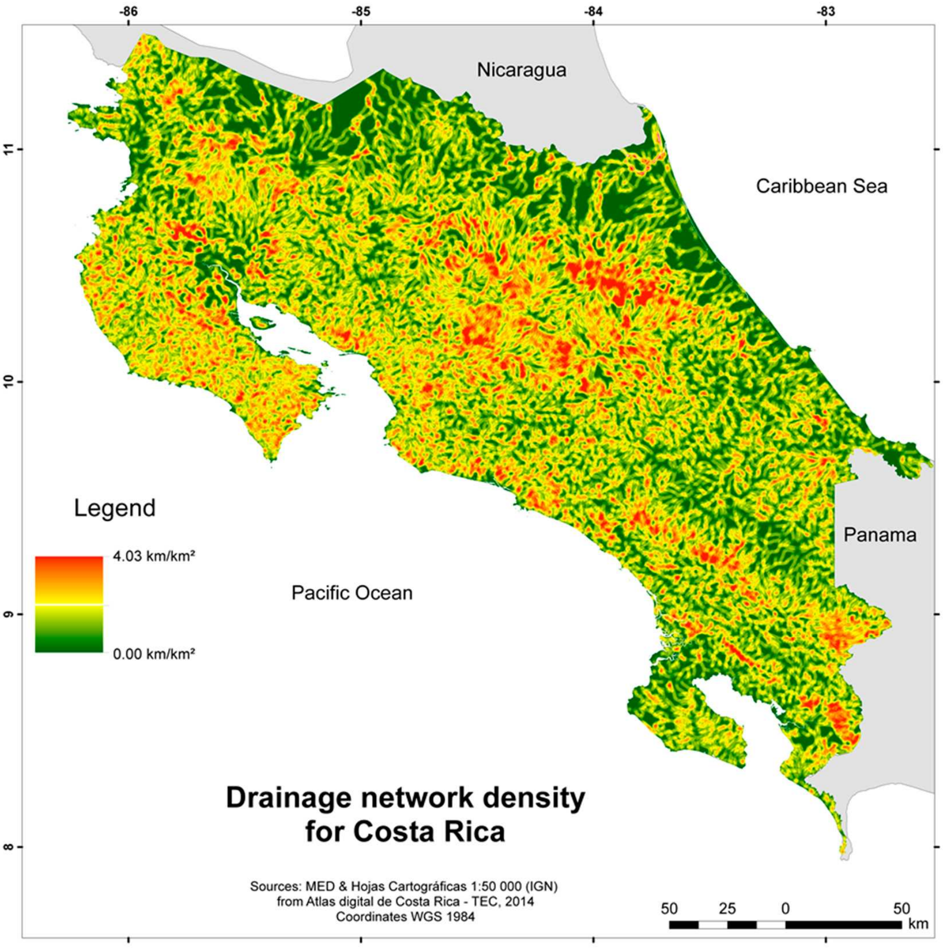

Figure 5. Drainage network density for Costa Rica based on the cartography maps (IGN) on a 1:50,000 scale digitalized by TEC [44].

3. Results

In this GIS-MCDA analysis, the problem is defined as the identification of sites with the best intrinsic conditions for SM in Costa Rica based on four criteria. The main result of this work is the suitability map presented in Section 3.4 (3.4. Suitable Areas).

3.1. Screening of Suitable Areas

Two criteria were considered for the screening of suitable areas: terrain slope and soil texture. According to the Costa Rican Forest Law 7575 [46], terrains with a slope higher than 40% are considered steep terrains. Also soils in a protected area are not available to any other activity other than conservation purposes (Organic Environmental Law 7554 [47]) and have no soil texture information as well. Soils falling into wetlands and beach classes are also excluded from further analysis in the screening process.

Suitable areas are considered regions where the terrains have a slope lower than 40% and with any soil type other than protected areas, wetlands and beaches. These areas were assigned the value of 1 while all other areas were assigned a value of 0. Both thematic layers are joined by an "OR" connector. This means that only when both values are 1, the screening map will obtain a value of 1. In any other combination, the assigned value is 0, thus, rendering the area not suitable for SM. The final screening map is shown in Figure 6, where suitable areas are shown in blue and unsuitable areas in grey.

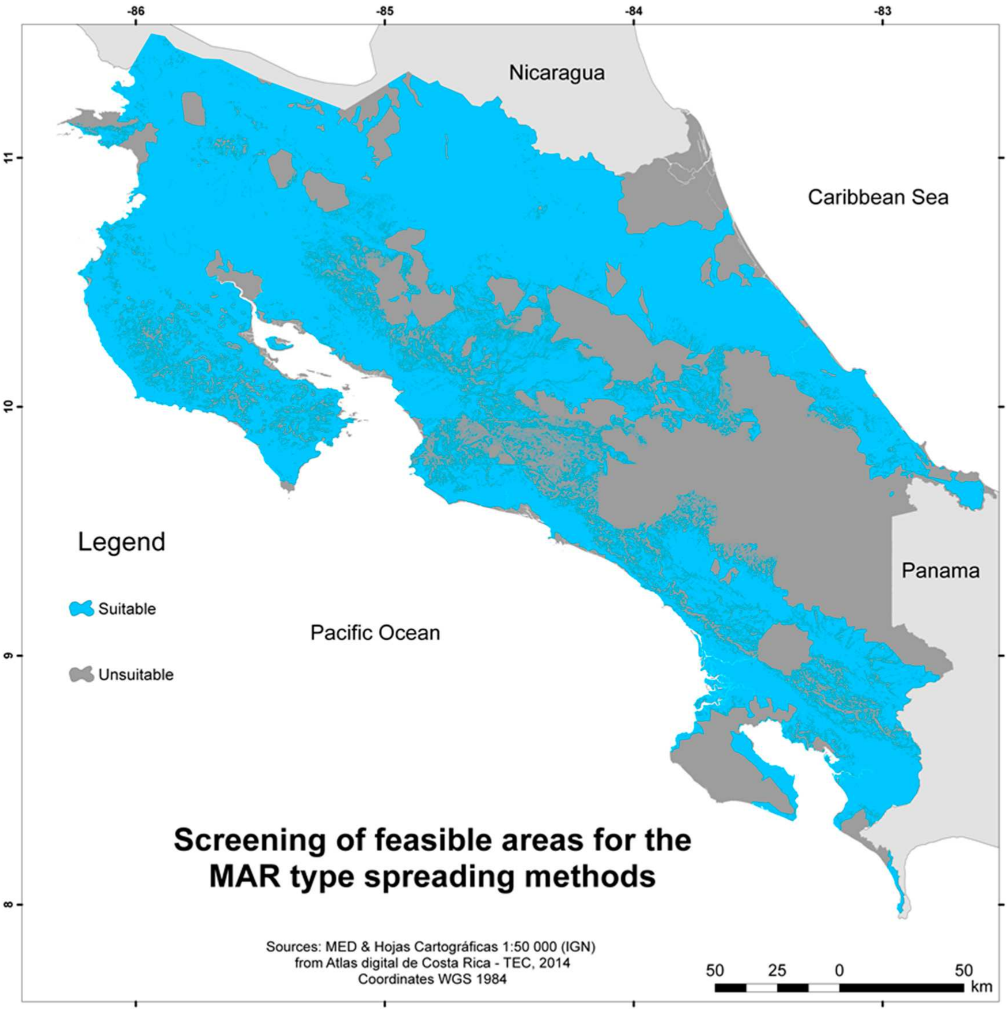

Figure 6. Screening suitable sites for SM in Costa Rica based on the terrain slope lower than 40% and protected areas, beaches, and wetlands.

The results indicate that more than half (61.0%) of the country's surface is suitable for direct surface recharge techniques. It can be appreciated in Figure 6 that the Northern and Tortuguero lowlands, as well as the Tempisque River Valley and the Nicoya Peninsula present the majority of available areas. Also along the Caribbean and Pacific coast and the Central and General valleys some large areas are identified as suitable. It is important to point out that more than a quarter of the country is under some kind on protection, thus, only conservation and investigation activities are allowed. The main mountain ranges systems (Guanacaste, Central, and Talamanca cordilleras) are excluded both due to their steep terrain and protection category.

3.2. Standardization

The four thematic layers were standardized in order to be implemented in the WLC. Step-wise functions are used for the hydrogeological aptitude and soil texture; for the terrain slope, a series of linear functions between the threshold values was used, and for the drainage network density a linear function throughout the range of the criterion values was used. Figure 7 shows the graphics for the standardization of each criterion. A short description of each criterion and their threshold values are given.

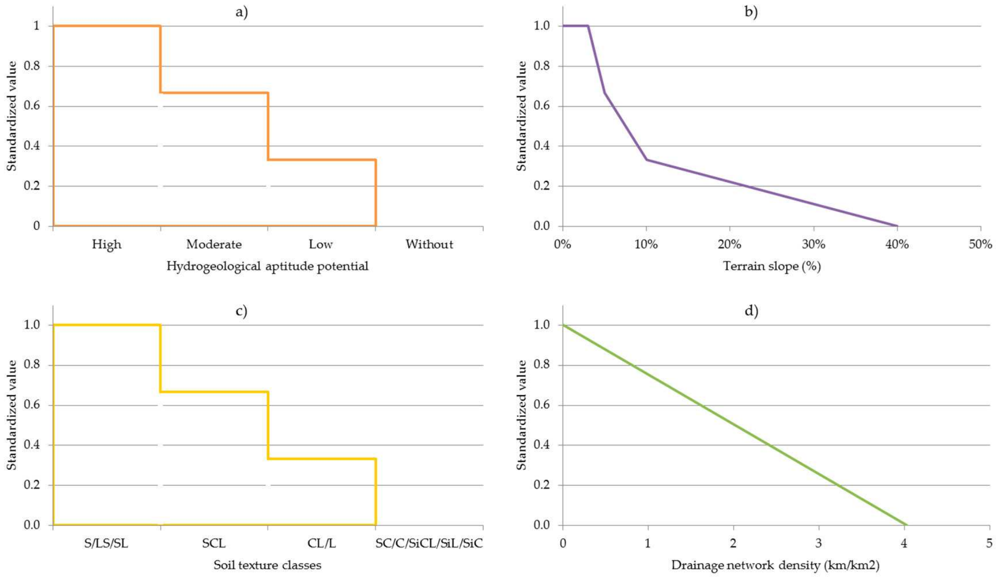

Figure 7. Standardization of the four criteria used in the WLC. (**a**) hydrogeological aptitude; (**b**) terrain slope; (**c**) soil texture; and (**d**) drainage network density.

The step-wise function is used for the hydrogeological aptitude maintaining the original classification (see Figure 7). Areas classified in [42] as without potential are assigned a value of 0; while areas with high, moderate, and low potential are equally distributed between 0.0 and 1.0. High potential areas are assigned a value of 1.0, moderate potential areas are assigned a value of 0.67, and low potential a value of 0.33. It is important to keep in mind that areas classified as "without potential" can still hold aquifers (e.g., fractured aquifers) [42].

Several different approaches to classify the suitability of the slope are available in the literature [12,16–19,21–23,25–34,41]. The linear function for the standardization of the slope is used in [12,41], all the others use the step-wise function (slope classes). A slope from 0 to 3% is considered optimum for infiltration schemes followed by three more classes (3% to 5%, 5% to 10%, and above 10%) [17,21,22]. Based on these classes, three breaking points are chosen for the terrain slope: from 0 to 3% a value of 1.0 is assigned, the next breaking point is at a slope 5% with a value of 0.67 and 10% with a value of 0.33, finally, values above 30% are assigned a value of 0.0. The standardization is given in Figure 7b.

The soil texture classification used is based on [20,22,30]. As it is shown in Figure 7c, the first class consists of sandy soils as sand (S), loamy sand (LS), and sandy loam (SL) which represent "High" infiltration capacity, thus a value of 1.0 is assigned. Sandy clay loam (SCL) is assigned a value of 0.67; clay loam (CL) and loam (L) a value of 0.33; and "Unsuitable" soils, which consist of sandy clay (SC), clay (C), silty clay loam (SiCL), silty loam (SiL), and silty clay (SiC) are assigned a value of 0.0.

The drainage density indicator is standardized using a step-wise function in [17,19,21,22,29]. The classification system used in [17,21] ranges from "good" or "excellent" (0–0.75 km/km^2) to "poor" (>2.5 km/km^2), with class limit increments of 0.75. Slightly lower limit values between the classes are given in [22], ranging from 0 to 0.5 km/km^2 as "good" to above 1 km/km^2 as "poor" and class limit increments of 0.5. In [19] a drainage density under 2 km/km^2 is considered favorable for MAR. A lower drainage network density category is used in [29] where values higher than 1 km/km^2 are unsuitable for MAR. All the classification systems discussed show linear increments in the class limits. Based on the linear distribution of the limits and the fact that the drainage network density is an indicator of terrains with good infiltration rate, but not of unsuitable infiltration sites, a linearization was done (see Figure 7d): a value of 1.0 was assigned to a 0 km/km^2 drainage network density and 0.0 to the maximum drainage network density (4.03 km/km^2).

3.3. Multi-Influencing Factor (MIF)

According to the MIF methodology, the more influence a criterion has on the other criteria and the objective, the higher is its score and higher the weight obtained. A total of six major effects and two minor effects where identified between the criteria (as well as between the criteria and the objective) and visualized in the diagram in Figure 8. The total cumulative score of 7 points is presented in Table 1 as well as the computation of the weights by the MIF method.

The hydrogeological aptitude criterion has three major effects: on the soil texture, on the drainage network density, and on the recharge process; the major effect on the soil texture is explained as the soil type is decisively influenced by the geologic parent material [42] while the major effect on the drainage density is due to the fact that the geology influences the development of river networks [21,22,39]. The terrain slope has two major effects: on the drainage network density and on the recharge itself; the steeper the slope, the higher is the drainage density in an area [22]. Soil texture has a major effect on the recharge process as well as minor effects on the drainage network density through erosion and deposition processes [21,22]. Drainage network density is considered as an indicator of the infiltration capacity of a specific area, thus, it only has a minor effect on the recharge process.

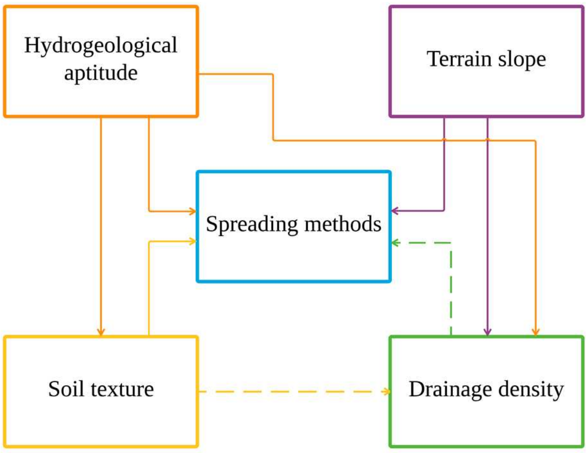

Figure 8. Interaction between the criteria for the MIF method (solid arrows represent major effects and dash arrows minor effects).

Table 1. Computation of the criterion weight using the MIF method.

Criterion	Score	Weight
Hydrogeological aptitude	1 + 1 + 1 = 3	43%
Terrain slope	1 + 1 = 2	29%
Soil texture	1 + 0.5 = 1.5	21%
Drainage density	0.5	7%
Total	7	100%

3.4. Suitable Areas

WLC is used in this work to overlay the criteria in order to identify and rank suitable sites for SM. The direct result of the WLC is shown in Figure 9, where the previously screened suitable areas (see Figure 6) are assigned values from 0 to 1 according to the WLC (color range from orange to green). The screened out or unsuitable areas in Figure 6 are also presented in grey in Figure 9.

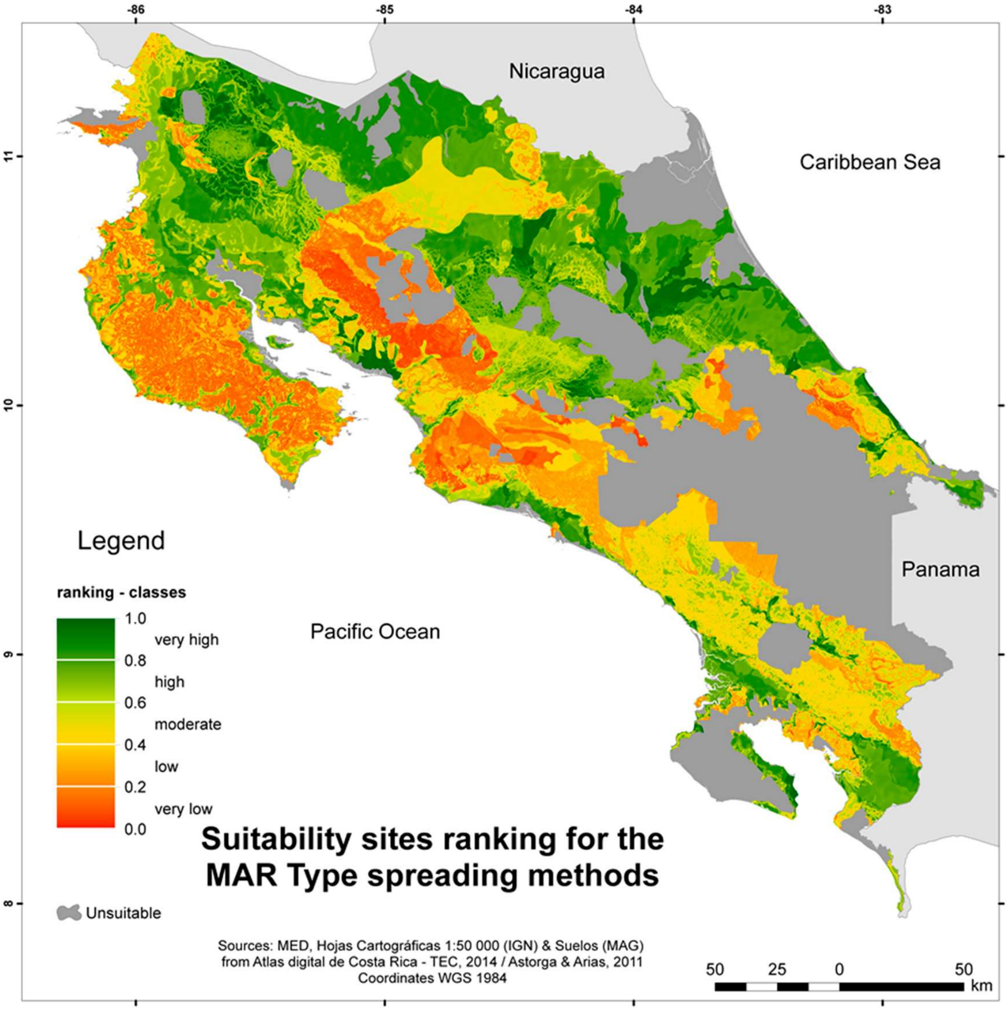

Figure 9. Costa Rica's areas ranking of site suitability for SM calculated by the WLC based on hydrogeological aptitude, terrain slope, soil texture, and drainage network density.

For a better interpretation of the identification of suitable areas for conducting the SM, the WLC map was categorized into five suitability classes according to the ranking value—the range is inside the parenthesis: "very high" (1.0–0.8), "high" (0.8–0.6), "moderate" (0.6–0.4), "low" (0.4–0.2), and "very low" (0.2–0.0). The percentage of both the suitable and total country area by class is shown in Table 2.

Table 2. Percentage area by category for the suitable areas and total country area.

Class (GIS-MCDA Range)	Percentage from the Total Suitable Area	Percentage from the Total Country Area
Very high (1.0–0.8)	20.4%	12.4%
High (0.8–0.6)	29.4%	18.0%
Moderate (0.6–0.4)	22.2%	13.5%
Low (0.4–0.2)	16.2%	9.9%
Very low (0.2–0.0)	11.8%	7.2%

Areas classified as "very high" and "high" suitable for SM in Costa Rica represent almost half of the suitable area previously screened in Section 3.1. This constitutes more than 30% of the total country area. "Moderate" suitable areas constitute more than one-fifth of the suitable area (13.5% of the total country) and areas classified with "low" and "very low" suitability constitute 28% of the suitable areas, which represents 17% of the total country area.

The Northern and Tortuguero lowlands still present most of the "very high", "high", and "moderate" areas in the country, while the Nicoya Peninsula is considered as having "low" and "very low" suitability as it is covered mainly by the Nicoya complex formation. Still, both banks of the Tempisque River are considered in the Northern Pacific with "very high" and "high" suitability. In the Caribbean coast, some areas are classified under the "very high", "high", and "moderate" suitability classes near the coast, but they change into "low" and "very low" when moving from the inland to the south. This behaviour is observed also in the Pacific coast where the lowlands fall into the "moderate" suitability category. The General valley mostly presents areas of "low" suitability for SM.

3.5. Sensitivity Analysis

The value range of the criterion weight by adding or erasing relationships in the MIF method is shown in a boxplot diagram in Figure 10. The original criterion weight obtained by the MIF method in Section 3.3 is presented as a blue line inside the boxplot, the new value for each criterion obtained by adding or erasing a minor effect are represented through the box and the major effects via the whiskers (extending vertical lines from the boxes) in Figure 10.

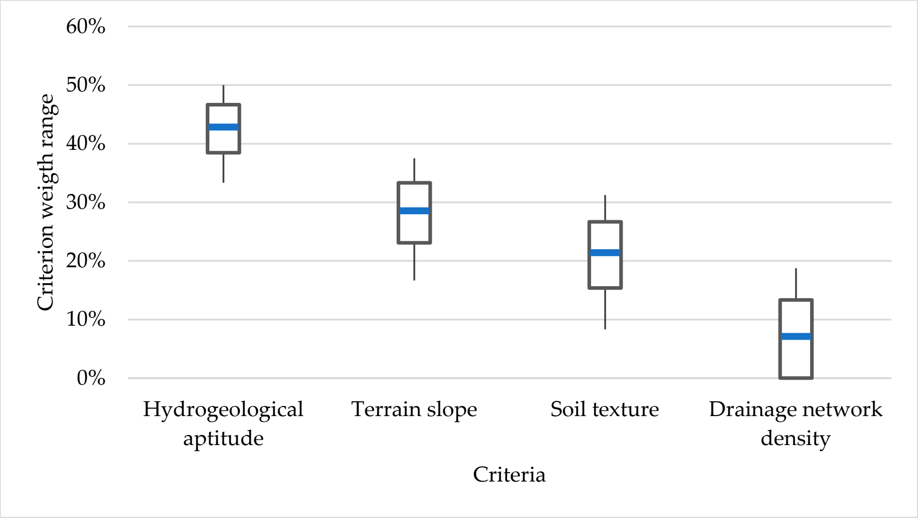

Figure 10. Range of weights used for the sensitivity analysis by adding or erasing one minor or one major effect between the criteria for the MIF methods.

By adding or erasing one minor or one major relation between the criteria in the MIF method, a total of eight scenarios with different decision rules are obtained. The changes in the weight of one criterion affect all the other criteria, thus, adding a relation to a criterion increases its weight and decreases all the other criteria weights, and the opposite occurs when one relation is erased. The eight scenarios are compared with the original reclassified WLC and the analysis is done by the areas that shift between classes.

The switch of classes or the percentage of the areas that change from one class to another is given in Figure 11 for each scenario, by adding and erasing one minor relationship. This change can be in any direction or not at all (e.g., no change)—the last being the ideal situation. Figure 12 shows the spatial distribution of the classes switch. A switch from a class with lower suitability to a higher suitability class is called a positive switch and from a higher suitability class to a lower is called a negative switch. Positive and negative switches are used in a directional context and not in a qualitative context: a suitability change from very high to high is a negative switch, but is not necessarily considered as a completely negative impact in the decision making.

In Figures 11 and 12 the "+" sign (a–d) stands for adding a minor effect and the "−" for erasing a minor effect (e–h), whereby HA represents the change in hydrogeological aptitude (a,e), TS in terrain slope (b,f), ST in soil texture (c,g) and DD changes in drainage density (d,h). The sensitivity analysis shows the hydrogeological aptitude as the criterion with less classes switch either by adding or erasing a minor relationship in the MIF, with the "no change" scenario representing 93.1% (a) and 94.5% (e) of the analyzed area, respectively. Hydrogeological aptitude is the criterion with the highest weight (see Table 1 and Figure 10).

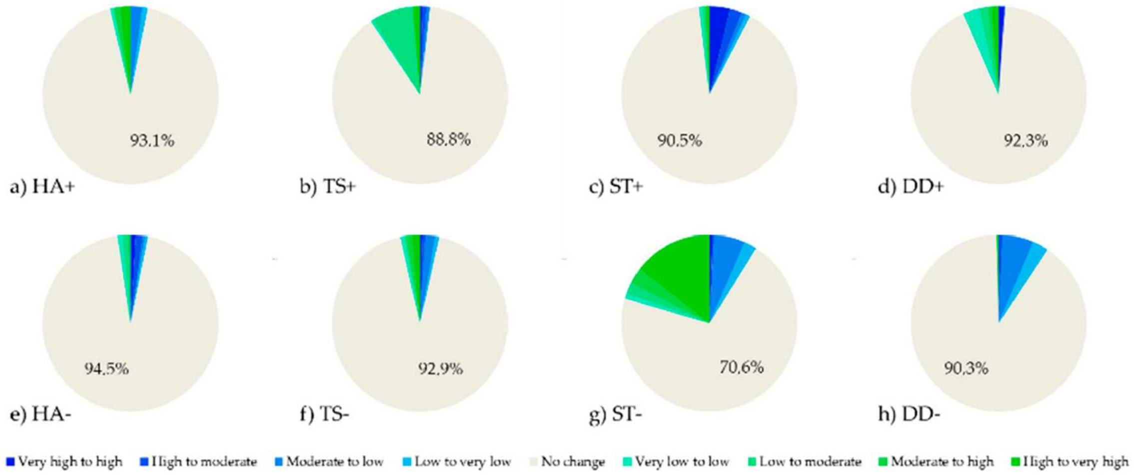

Figure 11. Classes switch for the sensitivity analysis on the criteria weight by the MIF method.

There are six scenarios where there is no change in the classes in more than 90% of the analyzed area (Figure 11a,c–f,h). The two scenarios where the switch between classes is higher than 10% (ergo no change under 90%) are when a minor effect is added to the terrain slope criterion (11.2% in Figure 11b) and when a minor effect is erased from the soil texture criterion (29.4% in Figure 11g). In the last scenario (ST−), erasing one minor effect from the soil texture criterion, almost half of the switch is from high to very high suitability (14.4%) which is a positive switch. This is not considered as critical as the objective of the study is to point out the areas that offer the best conductions for conducting SM. In other words, this work is inclusive, it is done to further research the areas classified as with very high, high, and moderate suitability, instead of being exclusive, were the objective will be to exclude study areas.

The second highest switch is achieved when adding a minor relation to the terrain slope criterion (11.2% in Figure 11b) which is also an increase in the classes, with 7.5% of the area changing from low to moderate suitability. This positive switch is also not considered critical as this work is inclusive. Two other switches present values above 5% (Figure 11g,h); both represent a negative switch from moderate to low suitability and both occur in 5.7% of the analyzed area. They are achieved when erasing a minor effect of the soil texture criterion and the drainage density criterion. All other switches represent less than 4% of the analyzed area. Based on this analysis, the uncertainty of the assign weights by the MIF method is considered acceptable.

In all the scenarios, the switch between classes is distributed all over the country (see Figure 12). The distribution of the switch classes is reciprocal within the criterion; they tend to be opposite for each pair scenarios per criterion, e.g., positive switch (blue regions) in Figure 12a turn to negative switch (green) in Figure 12e and vice versa. The reciprocal effect is a correspondence on a regional scale and not a "one to one" relationship per pixel.

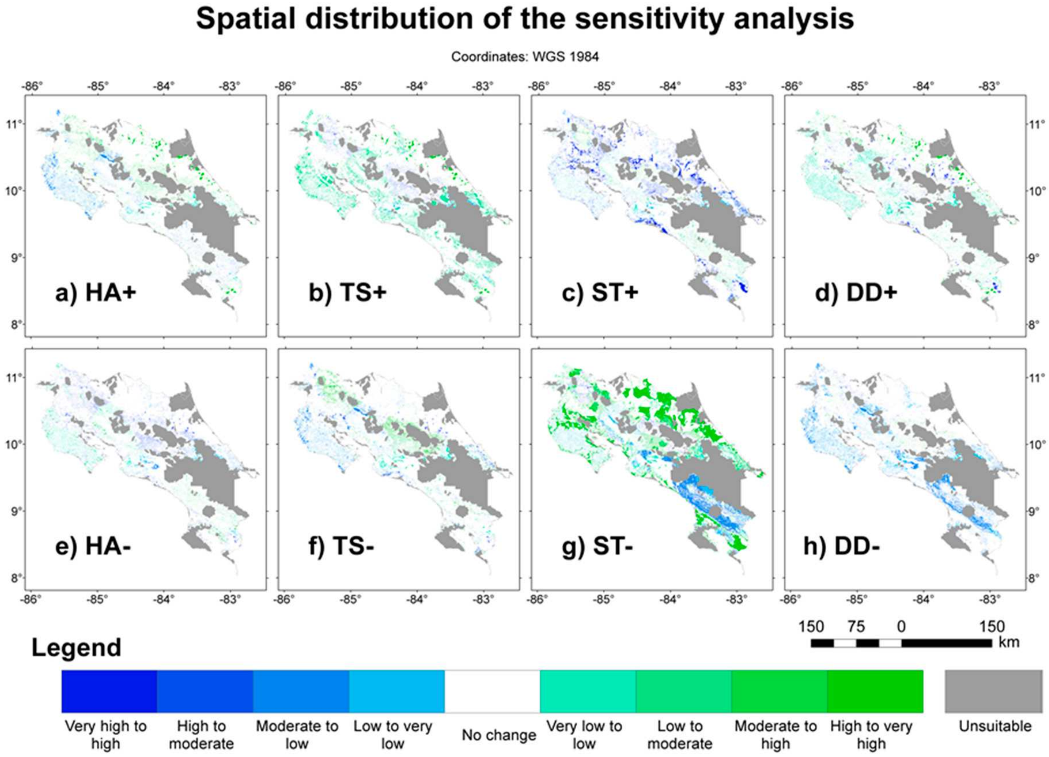

Figure 12. Spatial distribution of the sensitivity analysis scenarios.

The geographical distribution of the class title "without potential" for the hydrogeological aptitude criterion (see Santa Elena and Nicoya peninsulas in Figure 2) can be identified in Figure 12a,e. When a minor effect is added to the hydrogeological aptitude (HA+), the weight of the criterion increases, causing a negative switch in the mentioned region in Figure 12a. This is because this region has a value of zero in the criterion due to the standardization process (Figure 7a). The same outcome can be seen in the mountain ranges of the Guanacaste and Central cordilleras with the terrain slope in Figure 12b,f where slopes in the range of 10% to 40% have the lowest values (see Figures 3 and 7b).

The opposite occurs with a criterion characteristic with a high standardization value. The soil texture classes loamy sand, sand, and sandy loam concentrate in the General valley in the south of the country (see Figure 4). These classes are standardized with the higher value (1.0) within the criterion in Figure 7c. With the addition of a minor effect to the soil texture (ST+) the weight of the criterion increases, thus, areas with a higher value will show a positive switch as the General valley in Figure 12c. In Figure 12g, a predominance of negative switches in the same region can be noticed when a minor effect is erased (ST−).

The drainage density values are distributed all over the country (Figure 5) and no clear distribution can be observed in Figure 12d,h.

4. Discussion

The identification of the sites that present the best physical conditions in Costa Rica for the application of SM schemes is based on four criteria: hydrogeological aptitude, terrain slope, soil texture, and drainage network density. The results obtained in this study are an indicator of the suitability of an area in comparison to other areas in the country, but it does not mean that it is not possible to conduct infiltration schemes to increase the recharge in an area with a low ranking, e.g., "very low" or "low" suitability. It only means that it is plausible to have a better infiltration process in an area with a higher ranking.

Based on two criteria (terrain slope and soil texture), the suitable areas in Costa Rica for SM were screened. The suitable areas constitute almost two-thirds of the country's area (61%). The suitable areas were grouped in five classes for a better interpretation. Most of the country is classified as "highly" suitable for SM (18% of the country, 29% of the suitable areas).

The areas with higher suitability for SM implementation are located in the Northern and Caribbean lowlands, as well as in the Tempisque River Valley in Guanacaste, the former being also the region with most water scarcity problems reported in the last decade in the country [2]. Other areas with high suitability to hold recharge structures are in the Central and South Pacific coastal areas.

The suitability map is a tool for the decision maker, it should be used as a base map where other variables—such as water demand, availability of water resources, waste water facilities, etc. can be integrated to prioritized the sites for MAR implementation in Costa Rica. For example, this map can be used to identify the suitable areas for SM in a radius around the production wells of systems that need to increase their production in order to set the priorities for applying this method.

The scale and information used to assemble the suitability map is large and general, as it is the first attempt to classify and prioritize areas for further studies. Soil texture and hydrogeological aptitude maps limited in the working scale of the final map (both thematic layers were only available on a 1:500,000 scale); hence, this is the prevailing scale of the suitability map.

This map should only be used to emphasize the areas that possess the best physical characteristics for SM. Before any full-scale application is implemented, more precise and detailed information is needed, as well as working on a more appropriate scale, which will depend on the scope of the subsequent studies.

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Author Contributions: José Pablo Bonilla Valverde conceived and designed the general paper concept, analyzed the results, and wrote the first draft of the paper. Clemens Blank, Mario Roidt and Lisa Schneider processed the thematic layers and contributed to writing the Introduction and Materials and Methods. Mario Roidt provided additional revisions on manuscript. Catalin Stefan contributed to the conceptualization of the study and revised and provided feedback on the manuscript.

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8.2 Publication 2

Making the water–soil–waste nexus work: Framing the boundaries of resource flows

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Article

Making the Water–Soil–Waste Nexus Work: Framing the Boundaries of Resource Flows

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Abstract: The Sustainable Development Goals have placed integrated resources management, such as integrated water resource management, at the heart of their targets. The upcoming "International Decade for Action—Water for Sustainable Development", 2018–2028 has highlighted the importance of promoting efficient water usage at all levels, taking into account the water, food, energy, and environmental nexus. While integrated resource management approaches have been defined and applied for decades, nexus approaches are more recent. For these latter approaches to be implemented on the ground, their system boundaries need to be clarified. While the Water–Energy–Food Nexus focuses on sectors, the Water–Soil–Waste Nexus addresses linkages between environmental resources—namely water, soil and waste—to tackle sustainable management. In this paper, we analyzed integrated management systems and how their system boundaries are defined. From this we determined that in order for system boundaries to be applicable, they should be clear, wide and flexible. Based on this, we propose the boundary of the Water–Soil–Waste Nexus system. We use two case studies to exemplify the usefulness of these system boundaries.

Keywords: integrated water resources management; integrated natural resources management; integrated solid waste management; Water–Energy–Food Nexus; boundary

1. Introduction

In September 2015, the United Nations Member States adopted the Sustainable Development Goals (SDGs) to promote a global transformation towards more sustainability. The SDGs are more comprehensive than their predecessors, the Millennium Development Goals, which were often criticized for not adequately considering the environmental dimension of sustainability. Water and the integrated management of natural resources are important and interlinking subjects in the SDGs. Hence the United Nations General Assembly, as of 25th November 2016, encouraged member states and all relevant partners to contribute to the International Decade for Action, "Water for Sustainable Development", 2018–2028. The upcoming "Water Decade" builds on the momentum gained during the International Decade for Action, "Water for Life", 2005–2015, in order to support the implementation of the SDGs.

The discussion that resource management needs greater integration reaches beyond the SDGs. It is ongoing in science and intergovernmental meetings since the middle of the 20th century [1]. Integrated water resources management (IWRM) has a long history—of over half a century [2,3]. Consequently, and with the momentum of sustainable development in the 1990s, different integrated environmental management approaches appeared. Examples besides IWRM [3–6], are integrated natural resources management (INRM) [1,7,8] and integrated solid waste management (ISWM) [9,10]. In general, these approaches aim at optimizing the use of one compartment while considering its effect on related fields. Common to these approaches is a holistic view (e.g., INRM [11], ISWM [10], IWRM [12]) and a systems approach (INRM, IWRM [1], ISWM [10]).

1.1. *Definition of Concepts: Systems, Systems Analysis and Boundaries*

Holism requires systems analysis. Smithson et al. [13] mention that systems analysis is a method to investigate complex systems and define it as " ... the study of systems, for example hydrological systems, atmospheric systems and ecosystems in physical geography." (p. 752). A system is defined as "a set of interconnected parts which function together as a complex whole" ([13], p. 9). It is characterized by processes (e.g., fluxes), stores (e.g., a soil profile) and subsystems (e.g., groundwater in the hydrologic cycle) [ibid.]. The processes are often the key component to understand the system. In this article, we refer to processes as strictly (bio-)physical processes in the natural environment or in urban systems (e.g., water or waste fluxes).

Systems within the physical environment (see e.g., [13,14]) are located within a boundary [15]. Within this context, we understand the system boundary as the borderline (limit) that marks the geographic area (extent) of a system. It is the area in which physical processes are sought to be analyzed in systems analysis.

Environmental systems are most often so-called open systems, where matter and energy may transfer across system boundaries (both in and out) [15]. Examples are agricultural ecosystems or aquifer systems. Water enters and exits the system across their geographic boundary. The chosen boundaries define the system under analysis. In hydrology the chosen catchment size depends on whether the water system of a large river or of only one of its tributaries is analyzed. The inputs and outputs to the system can vary significantly depending on the chosen system boundary. Environmental systems are interlinked and often not easy to separate; yet when applying systems analysis, the system under investigation needs to be clearly described by defining its boundaries, for instance for the set-up of numerical models. Defining the boundaries is important and often challenging. Meadows and Wright [16] put clear words to it in saying that " ... if we're to understand anything, we have to simplify, which means we have to make boundaries" (p. 97). They go on to explain that " ... where to draw a boundary around a system depends on the purpose of the discussion"; and " ... the lesson of boundaries is hard even for systems thinkers to get. There is no single, legitimate boundary to draw around a system. We have to invent boundaries for clarity and sanity [...]" [ibid.]. It is exactly the purpose of this paper to describe the boundary of the water–soil–waste system in order to make the Water-Soil-Waste Nexus Approach (WSW Nexus) operational, yet keeping in mind that the scale of the WSW Nexus may not be identical to the boundaries of the WSW System (see on that issue e.g., [17]).

1.2. *The Rationale for Framing the Boundaries of Resource Flows*

As the definition of boundaries is crucial to systems analysis, a question that all approaches have to address is: what are the boundaries of a system within which the interlinkages can be most effectively grasped and analyzed? The integrated approaches under analysis in this article (IWRM, INRM, ISWM) have addressed interlinking principles within holistic management in the past decade (examples are [5–7,18], see also more detail in Sections 2 and 3).

In recent years the nexus debate entered the discussion of integrated management with the Water–Energy–Food Nexus (WEF Nexus) [19]. The novelty in this approach lies in revealing tradeoffs and synergies to be considered in decision making amongst sectors aiming at food, energy and water security [ibid.]. There are some examples of analyses and methods to assess the WEF Nexus (see [20,21]); yet Cairns and Krzywoszynska report that there is a “ . . . lack of clarity or consensus around the degree to which there is a recognizable ‘nexus methodology’.” ([22], p. 166). The WEF Nexus also does not seem to be clear regarding a boundary that marks something like a water–energy–food system (see also Section 2.5).

By focusing the debate on the interlinkages of resources and resource flows, the WSW Nexus intends to show the benefits of an integrated assessment and management of the resources soil, water and waste [23]. As an even younger concept than the WEF Nexus, the WSW Nexus is lacking a clear methodology for its implementation or operationalization on the ground as well as a common definition within which boundaries resources interlinkages are most effectively analyzed. With this present study we want to understand which elements are needed to make the WSW Nexus applicable to real world examples. A first step in systems analysis is the definition of the boundary of the system, with this in mind, we aim at assessing which boundary may be the most effective one when analyzing water, soil and waste flows of the water–soil–waste resources system.

To define the boundaries of the WSW Nexus as a new system we compare and contrast the question of boundaries of integrated management approaches that focus on any of the three resources: water, soil or waste. We attempt to describe the water–soil–waste resources system and its boundaries to derive the level at which the physical processes between water, soil and waste can be analyzed to create knowledge and eventually inform decision making in environmental governance.

The objectives of this paper are to (i) describe the systems of the integrated management approaches and the WEF and WSW Nexus, (ii) examine the boundaries of systems analysis in these approaches and draw lessons learned, (iii) based on this, propose the system boundary for the WSW Nexus and (iv) show—with two case studies—how this boundary is useful in the application of the WSW Nexus.

2. An Overview of Integrated Approaches Related to the WSW Nexus

Below is a brief description of the three integrated management approaches (ISWM, INRM, IWRM) and the two nexus approaches (WEF, WSW).

2.1. Integrated Solid Waste Management

ISWM grew out of the waste management constituency as an approach to handle the increasing amounts of solid waste generated in the developed world in the past decades. The idea is that the many options of waste management in collecting, transporting, treating and disposing of waste must not only be considered in simple comparisons, but scrutinized following an approach that can improve economic and ecological efficiency through systemic and scientific approaches [24].

The definition of integrated waste management is given in the prominent book, *Integrated Solid Waste Management* [9].

> “Integrated Waste Management systems combine waste streams, waste collection, treatment and disposal methods, with the objective of achieving environmental benefits, economic optimisation and societal acceptability. This will lead to a practical waste management system for a specific region.” ([9], p. 15)

In ISWM, it is not necessarily the case that one resource (waste) is integrated with other environmental resources. It is rather the integration of different waste materials, sources of waste, collection practices, as well as a combination of the varying treatment methods such as incineration, anaerobic digestion, landfilling or recycling [9]. The European Commission went beyond the goals of ISWM. In communication COM/2014/0398, the EU discusses the concept of the circular economy towards a zero-waste program for Europe. The overall scope of a circular economy approach in ISWM is to reduce residual waste streams as far as possible in order to close material cycles. This is an objective that is also aimed to be achieved in developing countries [25].

2.2. Integrated Natural Resources Management

INRM grew out of the agricultural constituency as a research and development paradigm. The approach of INRM is a systems approach that aims to impact the quantity and quality of more than one resource [1].

The definition we refer to in this paper of INRM stems from the Consortium of International Agricultural Research Centers (CGIAR), organized as a global agricultural research partnership with a similar structure to the Global Water Partnership (GWP). At its second workshop on INRM research in the CGIAR in 2000, the INRM approach was defined as:

> " . . . a conscious process of incorporating multiple aspects of natural resource use into a system of sustainable management to meet explicit production goals of farmers and other uses (e.g., profitability, risk reduction) as well as goals of the wider community (sustainability)". ([7], p. 5)

INRM is thus an approach that focuses on improving the life of farmers at the farming or household level through applied integrated research, participation, continued adaptation and learning.

2.3. Integrated Water Resources Management

Hydrologists and water engineers—familiar with systems analysis—used the increasing environmental awareness and global sustainable policy momentum in the 1990s to put forward the approach of IWRM [26] as a systems approach to the study of water resources [1] and an interdisciplinary and holistic way of managing them.

The approach was coined with milestones such as the Dublin Principles and the Agenda 21 in 1992, the foundation of the GWP and the World Water Council in 1996 and the decision to prepare integrated water resources management and water efficiency plans at the Earth Summit in Johannesburg 2005.

The definition of IWRM that is most widely accepted was given by GWP in 2000 stating that IWRM is:

> " . . . a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems." ([18], p. 22)

Today, IWRM is the leading and most widely accepted paradigm of water management. Even though controversially discussed and criticized the aim of implementing IWRM around the globe is ongoing, with varying levels of success. The dedication of SDG 6.5 to IWRM shows its high level of importance on the agenda in today's approaches to manage water resources [27].

2.4. The Water–Energy–Food Nexus

The increasing scarcity of water, food and energy and an increasing demand by a growing populations and changing lifestyles were called the "perfect storm" to arise in 2030 by Beddington [28], who strikingly described the inextricable linkages between the nexus compartments.

Some years later—with a report on the Water–Food–Energy–Climate Nexus by the World Economic Forum, the nexus conference background paper "Understanding the Nexus" by Hoff [19] and its proceeded conference on the WEF Nexus in Bonn—the WEF Nexus gained momentum in international organizations until today [29].

A generally agreed-upon definition of a nexus approach has not yet emerged. However, at the dawn of the nexus approach and in preparation for the Bonn 2011 nexus conference, the background paper prepared by Hoff [19] has greatly influenced the shaping of the approach. In his view, the WEF Nexus lies within the context of achieving water-, energy-, and food security in an emerging green economy. Within that context, the WEF Nexus aims to support such a transition through achieving greater policy coherence and higher resource use efficiency [ibid.]. Through reducing trade-offs and building synergies, the intentions of the WEF Nexus are to increase the security of water, energy and food, which would result in secure access for all the worlds people [ibid.]. This is based on three principals: (1) "investing to sustain ecosystem services" as they lay the basis of our needs as natural capital, which can draw on investment when incorporated into national accounting; (2) "creating more with less", as the green economy depends on amplified efficiency to combat resources scarcity; (3) "accelerating access, integrating the poorest" aims to reduce poverty, while accelerating development and sustainability ([19], pp. 14–15).

2.5. The Water–Soil–Waste Nexus Approach

The WSW Nexus is in close relationship to the WEF Nexus [30]. While the WEF Nexus focuses on sectors, the WSW Nexus asks how resources should be managed to tackle sustainable management [30]. In particular, the addition of waste as a resource dimension that often gets omitted in the sector based approaches shall arguably result in more effective and efficient solutions to problems. By moving away from sectors to resources, the possibility for a stepwise approach of the analysis of the varieties and options of resource interlinkages is given. First, natural science processes such as material fluxes and respective scenario building can be assessed. Then corresponding socioeconomic benefits can be determined for the respective scenario options. Ultimately, context-specific solutions and potential overarching policy recommendations can be developed and chosen.

The WSW Nexus Approach is described as follows:

> "The Nexus Approach to environmental resources' management examines the inter-relatedness and interdependencies of environmental resources and their transitions and fluxes across spatial scales and between compartments. Instead of just looking at individual components, the functioning, productivity, and management of a complex system is taken into consideration". [30]

The need and usefulness of the WSW Nexus is described by Hülsmann and Ardakanian [31] while Kurian and Ardakanian [32] assess the governance needs for the Nexus.

3. The System Boundaries of Integrated Environmental Management Approaches

In the following, we assess the boundaries of the previously described systems. We further describe their strengths and weaknesses in the context of the approach to draw lessons for the WSW Nexus.

3.1. Integrated Solid Waste Management

ISWM analysis takes place within municipal or intermunicipal boundaries that mark the waste system. The waste system is spatially comprised of the sources of waste, collection and transport as well as treatment including reuse, recycling or disposal [9]. It is apparent that this system is designed and operated by humans and is not spatially bound by environmental but social boundaries. ISWM aims to integrate the above mentioned waste related processes which mainly occur within the administrative boundaries of the municipality, also including the city or town level [33]. It is a strength of the waste system that in terms of waste flows within the municipality, the boundaries are clearly defined.

Several case studies and examples reflect these boundaries, such as the solid waste authority of the county of Palm Beach in the USA, the municipality of Kalundborg in Denmark [34], the city of Thessaloniki in Greece [35] or several other cities in Asia [36]. ISWM is also conducted in settings similar to municipalities such as the industrial park level in Tianjin city [37]. However, as the range of management options increases with integrated methods the boundary may also expand. McDougall et al. [9] describe that IWSM benefits from the economy of scale when organized on a larger level than a single municipality. They argue for an area upwards of 500,000 households. This requires combining waste streams of different municipalities which is already common practice since many years in several places around the world [ibid.].

Often the waste system does not operate strictly within a single municipality anymore with different processes (recycling, landfills, reuse) located outside a municipality's boundary [38]. In addition, the control of the waste management system is difficult, as waste management is often compartmentalized with several independent private operators that are in charge of collection or treatment steps [10]. Taking this into consideration expands the boundary of ISWM to an intermunicipal level wherever appropriate. For analysis of waste streams, it is a weakness that the boundary definition is prone to become ambiguous when it exceeds the municipal boundaries.

Waste systems can be analyzed by using Life Cycle Inventory Assessment [9] or Material Flow Analysis [39] approaches. Central to these methods is the definition of the boundary of the system. It is defined around the waste system, within municipal or intermunicipal boundaries.

3.2. Integrated Natural Resources Management

INRM is promoted mainly at a local level based on agroecosystems. However, a strong emphasis is also across different ecosystems and social boundaries. INRM focuses on the interactions of agricultural activities with the surrounding environment. On the one hand agricultural activities are to some extent derived and influenced by the conditions of ecosystems but are, on the other hand, heavily dominated by social arrangements rather than natural boundaries. Hence INRM aims to consider both boundaries.

The focus of INRM activity is often local. With its background in farming systems research, INRM seeks to build the capacity of farmers and other natural resources managers [40], while placing the farmer at the household or field level at the center of activities [41,42]. This is as strength in the approach, that when systems analysis is being conducted the farm level provides a tangible and practical boundary definition.

When looking at INRMs key principles, it can be seen that the approach reaches beyond the boundary of the farm level. INRM aims for "multiple scales"—spatially and temporally. Well aware of the complexity, Sayer and Campbell [43] recognized a biophysical component reaching from the single farming plot to the global level. In further descriptions of the approach the focus remains on the multitude of scales with the ecosystems as boundary of influence [39]. Hence ecosystems, or agroecosystems of varying sizes from plot level to ecozone or social units from the village to national level that cross scales and boundaries are discussed [42].

The boundary around the ecosystem or agroecosystem seems to remain constant. Yet the spatial dimension of scale is unclear (multitude of scales) and the boundary of the ecosystem seems unpractical when exceeding the farm level.

Examples of the INRM paradigm can be seen from case studies where the focus of analyzing the system was often local. Hagmann et al. [11] show how research spanned from the plot level up to the policy sphere. Different agricultural techniques were implemented at the farm level, such as soil fertility and water conservation. Afterwards, efforts were made to scale up to community, catchment or district level. Douthwaite et al. [40] introduce agricultural research projects on subcounty (in Uganda), village (in Nigeria) and pilot site scales (in Zimbabwe).

3.3. Integrated Water Resources Management

In IWRM, the boundaries for analyzing water resources is usually the river basin or catchment, derived from the water system i.e., the hydrological cycle. As water moves defined by natural boundaries, water quantity and quality can best be studied within the boundaries of the basin or catchment. As the approach of IWRM was derived from hydrologists and water engineers [26], the natural boundary of the basin is the preferred at which to assess water flows in contrast to socially constructed boundaries such as administrative borders. It is considered a strength of the approach that analysis of the water system is done bound by the basin as it is hydrologically speaking the most useful idea.

That the basin is the logic unit for IWRM was consolidated in the Dublin Principle Nr.1, the Agenda 21 (Chapter 18.9) and in the defining work of GWP [18]. It further received positive attention in subsequent meetings such as the World Water Forums, the International Freshwater Conference in Bonn (2001) or the Johannesburg Earth Summit 2002 [44]. Since then, the basin as management unit in IWRM is widely accepted [12,44–47].

Major objectives of IWRM concerning the basin are the development of river basin plans and the establishment of river basin organizations. However, the World Water Development Report 2012 states that the implementation of these objectives to prepare and implement IWRM plans "remains unsatisfactory and well behind target" ([48], p. 139).

Hence, in recent years these objectives have received critique and it is questioned whether the basin is the appropriate unit to manage water resources. Many also warn to impose a common framework without bearing in mind the local or national specifications and are skeptical towards the capability of river basin organizations or countries to implement IWRM in an effective way [49].

Firstly, the critique concerns the problem of fit. Intangible values of economics and societies that reach beyond the edges of a river basin complicate the process of IWRM [50] and create a complicated overlapping of authorities in decision making [45]. The creation of river basin organizations as a solution may increase not only political resistance and radically different socioecological situations, but also raises issues of democratic representation and legitimacy (ibid.). Graefe [44] describes the shift to IWRM as a "depoliticizing of water management" with "expert environmental administrators" as decision makers rather than governments (p. 26).

Secondly the justification for the basin as a boundary of water is being challenged as variables can surpass the river basin boundary. Water physically flows beyond the river basin through interbasin transfer projects (14% of global water withdrawals). This is likely to quadruple institutional management complexity [51]. In addition, the concept of virtual water demonstrates how water is indirectly diverted between basins around the globe [50].

On the one hand, some cautiously question if the basin is the only appropriate unit in its broad sense for IWRM and show examples where nonintegrated management was successful to argue that alternatives to IWRM may not be ignored [52]. On the other hand, IWRM is heavily criticized for its "basin fetishism" and it is warned from privileging only one scale to the increasingly complex tasks of water management ([44], p. 26). What is hydrologically useful is altered due to human activities, revealing the weaknesses of systems analysis by using the basin as the boundary of water flows.

Despite the scholarly debate, assessments in the context of IWRM such as the modelling of surface water and groundwater quantity and quality and other processes are based on the water system and hence the river basin or catchment is still the preferred boundary when analyzing water resource flows.

3.4. Water–Energy–Food Nexus

The question of boundaries in the WEF Nexus is not straightforward. While several authors address the issues of scales, there is no consideration or description of what exactly the water–energy–food system is and by which boundary it is enclosed. The dimensions of the WEF Nexus—even more than in the upper approaches—occur through their interlinkages at various and overlapping scales. It is widely accepted so far that the WEF Nexus must understand and address its dimensions across all scales; what this means and how this is connected to system boundaries remains unclear.

In contrast to other system approaches, the WEF Nexus has to consider and understand three different systems or sectors—agriculture, energy and water—and the interlinkages occurring at different and overlapping levels. Leck et al. [29] describe that interventions through the food, energy or water sectors need to carefully consider the entry point. This makes the consideration of boundaries so central to the Nexus Approach (ibid.). That the WEF Nexus considers the interlinkages of these three critical sectors is indeed a strength of the approach.

After the WEF Nexus gained popularity in 2011, it seems to be the common understanding that the Nexus Approach must be considered at all scales or across scales respectively [19,29,53,54], or at least at different scales [20,53,55]. What is exactly meant with the term "scale" in these cases is ambiguous. Authors refer to scales e.g., in terms of governance and decision making [19,29,54], local, national, global etc. [19,20,53,54] or spatial scale [19,20,29,53,54]. The authors do not further describe these terms. When speaking of scales, no boundary considerations are made that explain the extent of the water–energy–food system and clarify how systems analysis can investigate the WEF Nexus.

4. What Is Different This Time?—The Boundary of the Water–Soil–Waste Nexus System

The three integrated approaches (INRM, IWRM, ISWM) discussed above have some commonalities regarding the boundaries marking the respective system (see Table 1). They consider the system boundaries of the central compartment marking what system is analyzed, including interlinkages to related compartments or resources. For example, in IWRM the water system is often analyzed within the boundaries of the basin in which its interlinkages with land and other related resources are assessed. The WEF Nexus reveals that the interlinkages of the three sectors are increasingly complex as interlinkages range from a local level (e.g., villagers' deforestation for fuel resulting in decreasing water quality of local water resources through erosion) to a global level (global trade in fossil fuels, bioenergy, food and virtual water). Drawing distinct boundaries to assess those varying levels of interlinkages to assess their trade-offs and synergies basically becomes impossible.

Table 1. Integrated management approaches consider different systems and boundaries for their systems analyses and entail different strengths and weaknesses.

	ISWM	INRM	IWRM	WEF Nexus
Considered system	Waste system	Agricultural system	Water system	Water-, Energy-, Food System
Derived from	Municipal administration	Ecological and administrative boundaries	Hydrologic cycle	
Boundaries	Municipality to intermunicipality	Farm to ecoregion	Catchment (any size) to river basin	Multiple and unclearly defined
Strengths	Clearly defined by municipal boundaries	Tangible focus on the farm level	Hydrologically useful	Considers critical and interlinked sectors
Weaknesses	Boundary definition is ambiguous when exceeding the municipality	Unclear or unpractical use of boundary considerations when exceeding the farm level	Altered hydrological usefulness through interbasin transfer (real and virtual water)	Boundaries are not explained or defined.

When analyzing the interlinkages of water, soil and waste, how are the boundaries to be drawn? From the analysis above (see Table 1), we discovered that the water system, e.g., within IWRM, is analyzed at the basin or catchment level; the soil system, as per INRM, functions from farm level to ecoregion; and the waste system, as in the ISWM, is analyzed within the boundaries of a municipality or between them. We learned from the analysis of the integrated systems that the boundaries of the systems need to be (a) wide enough (to avoid microanalyses of plot levels as in some cases of INRM), (b) clear (to avoid confusion as in the WEF Nexus), and (c) flexible enough to accommodate varying needs (to avoid geographic constrictions as is the case of the basin discussions in IWRM).

The goal of the WSW Nexus is to increasingly understand the interlinkages between the three resources: water, soil and waste. Analyzing the WSW Nexus within the boundaries of only the watershed, just an ecosystem or exclusively within a municipality, will not necessarily properly consider the WSW Nexus system as a whole and hence not be wide enough. However, to be as clear as possible, the WSW Nexus will have to operate within the smallest common geographic area of the physical interlinkages of the three resources, e.g., at the overlap of the resources systems under investigation. The overlap of the two or more resources systems and thus their interlinkages vary significantly depending on the context they are investigated at thus allowing for the needed flexibility of its boundary. We define the boundary of systems analysis under the WSW Nexus as the geographic area where at least two systems overlap and thus form the WSW Nexus system.

Whereas processes within each of the resource's systems, namely the water system, the soil system and the waste system, will have to be analyzed, they are considered to be external to the system of the WSW Nexus and their results will be considered as external inputs (see Figure 1).

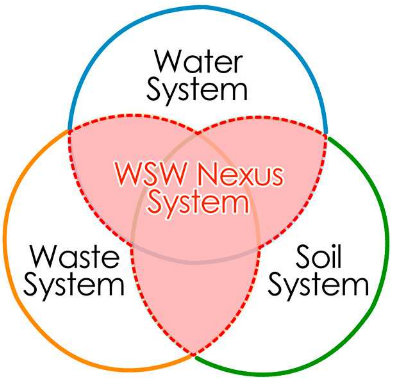

Figure 1. The water–soil–waste (WSW) Nexus system as the area where at least two resources systems overlap.

The results of the processes occurring within each system analyzed within their respective boundaries, i.e., water at the basin level, soil at the farm level, and waste (water) at the municipal level, will serve as input values to the WSW Nexus system. Of particular interest are the points in a resource flow or chain, where the interaction of the two systems is apparent. The WSW Nexus system itself will however not carry out the relevant analyzes of the processes of the underlying individual resource systems (e.g., hydrological modelling of the catchment to assess the changes in flow). The WSW Nexus system will take these external values, from the respective systems specialists, as drivers and inputs to the analysis of the interlinkages of the overlap.

The analysis of physical interlinkages within this system should ultimately aim at revealing benefits through increased resource use efficiency. There are different examples of benefits due to increased resource use efficiency. They can be direct efficiencies such as enhanced crop yields due to application of recycled nutrients or irrigation strategies, increased water productivity through industrial reuse or reduced waste (sludge, wastewater) from wastewater treatment plants through reuse. Resource use efficiency can however also extend towards more indirect, socioeconomic benefits such as food and energy security, increased public health and better risk management.

5. Illustrating the Boundaries of the WSW Nexus System—Case Studies

The WSW Nexus has so far not been applied extensively in situ. Below we will consider two cases to showcase the added value of assessing resource flows in an interconnected manner under the WSW Nexus. They illustrate how the boundaries of the WSW Nexus system facilitate assessing the interlinkages of these resources and material fluxes.

The first case study (see Section 5.1) illustrates a problem that is typically assessed in a disconnected manner either at the catchment level, a farm level, or within a municipality. By assessing resource fluxes individually, other resource flows and respective benefits are omitted. We argue that assessing interconnected resource flows opens up avenues for asking different questions and therefore also obtaining new answers, such as safe wastewater reuse in agriculture for enhanced yields, or managed aquifer recharge through interbasin transfer. The view through the lens of the WSW Nexus boundaries helps on the one hand to assess these resource flows in this new context, but restricts this analysis to a clearly defined geographic area on the other hand, thus reducing unnecessary complexity of the problem. By considering the inputs of the respective water, soil and waste systems as external factors and drivers into the WSW Nexus system, the issue of the boundaries of those systems is deferred to the respective systems and thus the respective subject matter experts (e.g., hydrologists to determine the size of the catchment to assess the water quantity entering the WSW Nexus system).

The second case study (see Section 5.2) shows the WSW Nexus system on a confined geographic area, that of an industrial park. Again the perspective of the WSW Nexus helps assess resource flows in combination, in this case those of water and waste (water), instead of analyzing each resource system independently. By doing so, clear benefits can be derived. The material flux analysis reveals benefits in the form of freshwater savings and reduced wastewater disposal necessities. The view through the lens of the WSW Nexus system helped disclose these benefits.

5.1. Mexico City and Mezquital Valley

5.1.1. The Benefit of Interlinked Resource Assessment under the WSW Nexus

With more than 20 million inhabitants, rapidly growing Mexico City is among the world's largest metropolitan areas. This has caused serious human and environmental health concerns going far beyond its administrative municipality's boundary, e.g., [56–58]. As the city has no wastewater treatment system, a 32 km long tunnel (6 m in diameter) was constructed in 1900 to take rainwater and wastewater from the naturally closed drainage basin of Mexico City to the Mezquital Valley situated 80 km north of the city.

About 60 m^3/s is discharged into the Mezquital Valley by the network of channels and tunnels [59]. The Mezquital Valley is the largest agricultural area irrigated with untreated wastewater in the world, with an area of 90,000 ha [60]. The use of wastewater represents a valuable resource in regional agricultural production, due to: (i) the continuous supply of irrigation water; and (ii) the repeated nutrient input to the soil [61]. As a result, wastewater irrigated agriculture provides five times the maize yield (10.0 t/ha) than rainfed maize (2.0 t/ha) [62,63]. Other crops such as lucerne or fodder oats as well as vegetables are also produced. Three agricultural districts (Tula, Alfajayucan and Ajacuba) are directly benefitting from this wastewater irrigation scheme [63]. In terms of water balance, Hernandez-Espriu et al. [59] further pointed out that the transition from unmanaged to managed aquifer recharge is expected to provide multiple benefits to the inhabitants of the valley.

Several scientific studies describe specific impacts of serious health-related and environmental issues [61] and support the recent opinion of Siebe et al. [63], who concluded there is a need to improve the ongoing management of the system.

5.1.2. The Boundaries of the WSW Nexus

Assessing the interlinkages of the resources water, soil and waste reveals agricultural benefits within the Mezquital valley. If we limit our toolbox to the known systems analyses (INRM, ISWM, IWRM), defining the optimal boundaries for the analysis of interconnected resource flows becomes difficult.

(1) Water: Basin boundary—not (or partly) applicable (interbasin transfer; anthropogenic wastewater transfer from the endorheic basin of Mexico City to the neighboring basin of the Mezquital Valley).
(2) Soil: Plot level or agroecosystem level—partly applicable (considering wastewater as an input into the system).
(3) Waste: Municipal administrative boundary—not applicable (the wastewater that is produced in one state is transferred to another: Mexico state vs. Hidalgo state).

Therefore, all the existing approaches defined by a resource-specific boundary (INRM, ISWM, IWRM) are failing in the attempt to capture the boundaries for the assessment of resource flows in this case. The WSW Nexus system, being defined as the geographic area where at least two systems overlap, in this case relates to the fields (soil system) that receive the wastewater (waste system) from Mexico City. The WSW Nexus system reveals benefits through increased resource use efficiency, which in this case is given by the increased yields in the areas irrigated with wastewater. Figure 2 describes the WSW Nexus system of this case study in a conceptual way.

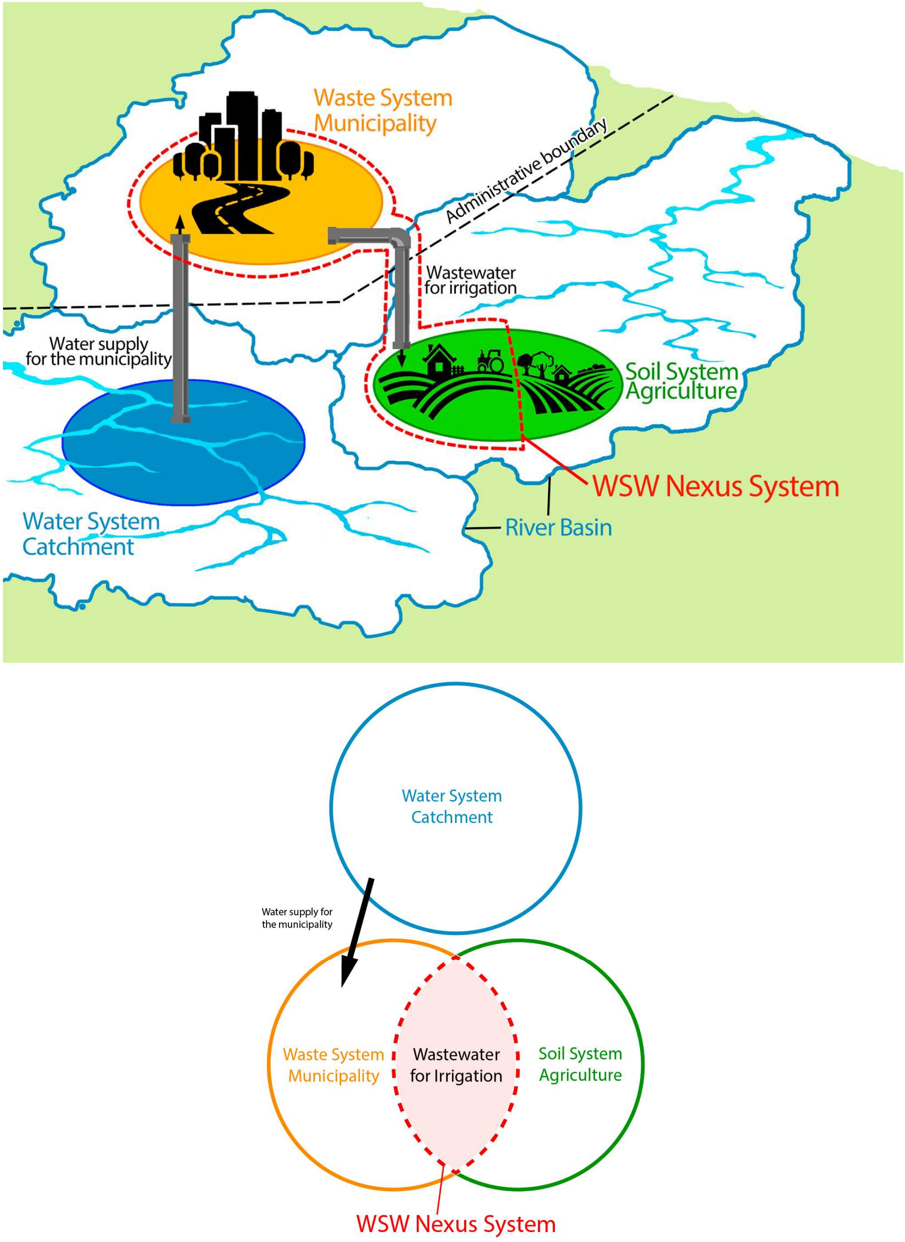

Figure 2. The WSW Nexus system is bound by the overlap of the wastewater system of the municipality and its use for irrigation on the soil system of the agroecosystem. The water system is external to the WSW Nexus system providing the water to the waste system. (The figures show a concept and do not reflect actual geographic information).

In this system, we consider the amount of water entering the overall water–wastewater scheme (81.9 m^3/s) as an external input from the water system to the WSW Nexus system [64]. The same applies to the inherent condition of the soil (e.g., nutrient content, type of soil, etc.) or the quality of the wastewater (e.g., existence of treatment system). This intends to reduce the overall complexity of the analysis to be able to focus exclusively on the interconnections of resources to reveal benefits of combined assessment. The boundaries of the respective water, soil and waste systems are however still defined by their respective scholars (e.g., the plot level for assessing soil fertility changes by soil scientists).

5.2. Mourcheh Khort Industrial Park

5.2.1. The Benefit of Interlinked Resource Assessment under the WSW Nexus

The model settlement Mourcheh Khort is an existing industrial park in the Isfahan province in central Iran, which is used to develop an eco-industrial park (EIP) concept through industrial symbiosis as part of a German–Iranian IWRM research project [65]. Mourcheh Khort is located about 50 km north of the city of Isfahan in the catchment area of the Zayandeh Rud. Approximately 500 small and medium sized industrial units with in total 17,000 employees from the food, metal, mineral, textile, plastics, paper and chemical industries are located on 582 hectares.

Process water in the model settlement originates partly from a central supply network fed by a large deep well but mainly from private wells at each factory. Groundwater from these wells is often pretreated by reverse osmosis on-site to reduce salinity and hardness. According to interviews with industry managers, water tables of private wells have been dropping severely due to overuse and drought in the past years (pers. comm. W. Raber with industries in Mourcheh Khort, 2016).

Wastewater from industries is mainly disposed to the sewage system connected to a central treatment plant constructed in 2011 [66]. However, particularly industries with small wastewater production dispose their water often by tankers outside of the industrial park, in order to save costs for connection to the sewage system (pers. commun. W. Raber with Park Management Mourcheh Khort, 2016).

The anthropogenic cycles of the industrial ecology follow three principles of interrelating mechanisms: (a) the bilateral principle (simple connection between two industries), (b) the nucleus principle (connection from one to several other industries), or (c) the cascade principle (a comparatively complex series of bilateral links) [67]. A material flow analysis (MFA) was applied to quantify the industrial water use applying STAN (subSTance flow Analysis, [68]).

The results of the case study (see Table 2) show that depending on the interlinking principle, a different stage of water-saving efficiency can be achieved. The focus of industrial symbiosis is on beneficial interfaces between companies through their material fluxes with the overall scope of a circular economy for water, waste, energy, and information. In this way, industrial symbiosis can be considered per se as a Nexus based concept. A view on industrial symbiosis under a Nexus Approach leads to a changed perspective on substances and energy cycles, from the life cycle of a product or service to the life cycle of a resource as compartment of the natural capital [69]. From our point of view, the discussed bilateral, nucleus and cascade principle can be used to assess different types of resource flows within the WSW Nexus.

Table 2. Potential reductions and savings in water consumption and wastewater production relative to the different interrelating mechanisms of the eco-industrial park (EIP).

Principle	Industries Connected	Reductions and Savings
Bilateral principle	Polyamide fiber production → dyeing factory	Fresh water consumption can be reduced by 33% of the total water demand of the two industries
Nucleus principle	Milk powder production (nucleus) → multiple connected industries (consumers)	Fresh water savings potentials of 92% and sewage savings of 67%
Cascade principle	Polyamide fiber production → poly-tube production → two different metal processing plants	Total savings of approx. 56% of the fresh water demand and approx. 83% of the wastewater

5.2.2. The Boundaries of the WSW Nexus

The scope of the case study was to assess the benefits from assessing the resources water and waste in an interlinked manner in order to close the wastewater cycles between the companies. Different EIP design scenarios considered varying levels of interindustrial water reuse without additional water supply for the connected water fluxes.

This case study shows the benefit-scale at the sublocal level in an industrial park. The two systems of water and waste overlap with the boundary of the industrial park itself. Figure 3 describes the WSW Nexus system of this case study in a conceptual way. It shows an example of one modeled scenario in the industrial park, where wastewater from one industry can be used as process water in several other industries.

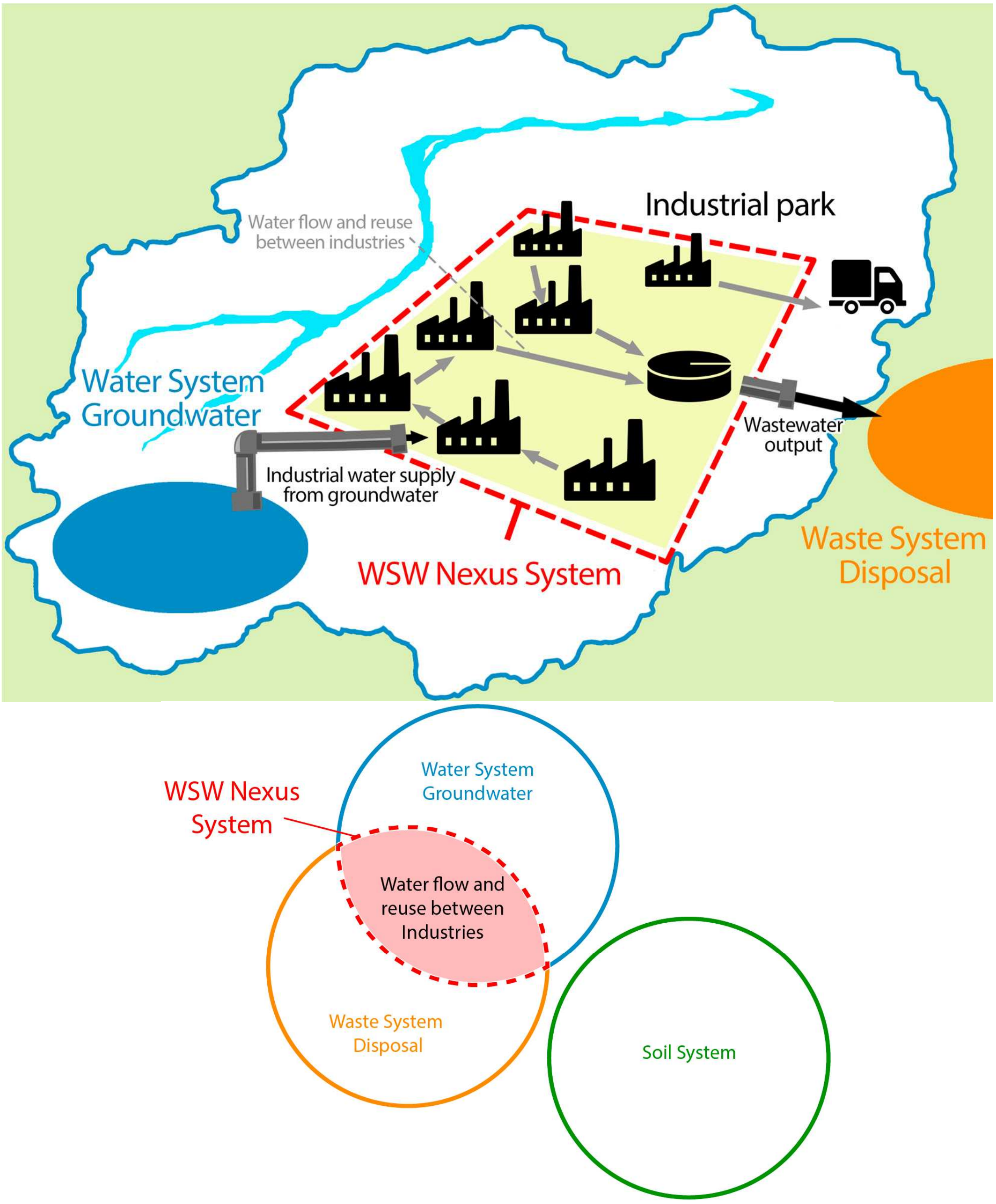

Figure 3. The WSW Nexus system is bound by the overlap of the water and the waste system where wastewater can be reused by other industries as intake. The soil system is external to the WSW Nexus system. (The figures show a concept and do not reflect actual geographic information).

6. Conclusions

In this study we examined the boundaries of systems analysis in ISWM, INRM, IWRM and the WEF Nexus. We derived three criteria for defining systems boundaries for integrated management, namely: wide, clear and flexible. The WSW Nexus system is designed to fit those criteria. It reduces the overall level of complexity of the nexus problem without ignoring that the complexity is inherent to each of the three underlying systems.

This deliberately stands in contrast to prominent thoughts in the WEF Nexus community (e.g., [19,21,53,54]). The unmanageable complexity of the WEF Nexus has been criticized (see e.g., [1,29]). The WSW Nexus system as described here intends to provide a clear definition. We are conscious of the fact that the analysis of (bio-)physical interlinkages alone is not sufficient to achieve sustainable management. Socioeconomic, political, and institutional aspects need to be taken into account as well. Nonetheless, we consider (bio-)physical interlinkages to be the basis for any further analysis. Going forward, the concept of the WSW Nexus system can be elaborated on by moving from the biophysical interlinkages towards their implications of socioeconomic and political issues, thus creating a "benefit-shed". It remains to be assessed if the boundaries of the WSW Nexus system are as useful to these further dimensions as they are to the assessment of interlinked resources.

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Conflicts of Interest: The authors state no conflicts of interest.

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8.3 Publication 3

How will environmental systems analysis inform the Water-Soil-Waste Nexus in 2050 to support Sustainable Development?

M. Roidt, T. Avellán, J. Seegert, P. Krebs

International Conference on Sustainable Development 2017, Columbia University, New York City.

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How will environmental systems analysis inform the Water-Soil-Waste Nexus in 2050 to support Sustainable Development?

Mario Roidt,[1,2] Tamara Avellán[2], Jörg Seegert[1], Peter Krebs[1]

[1] Technische Universität Dresden, Germany
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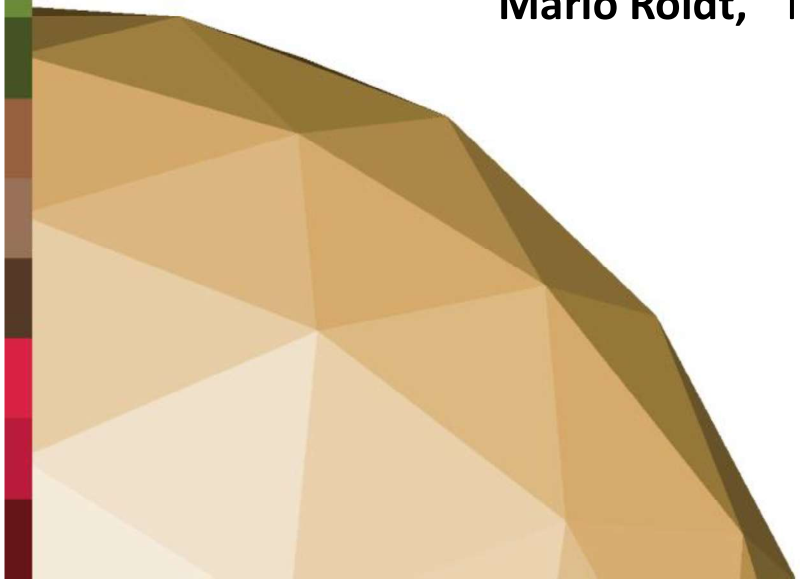
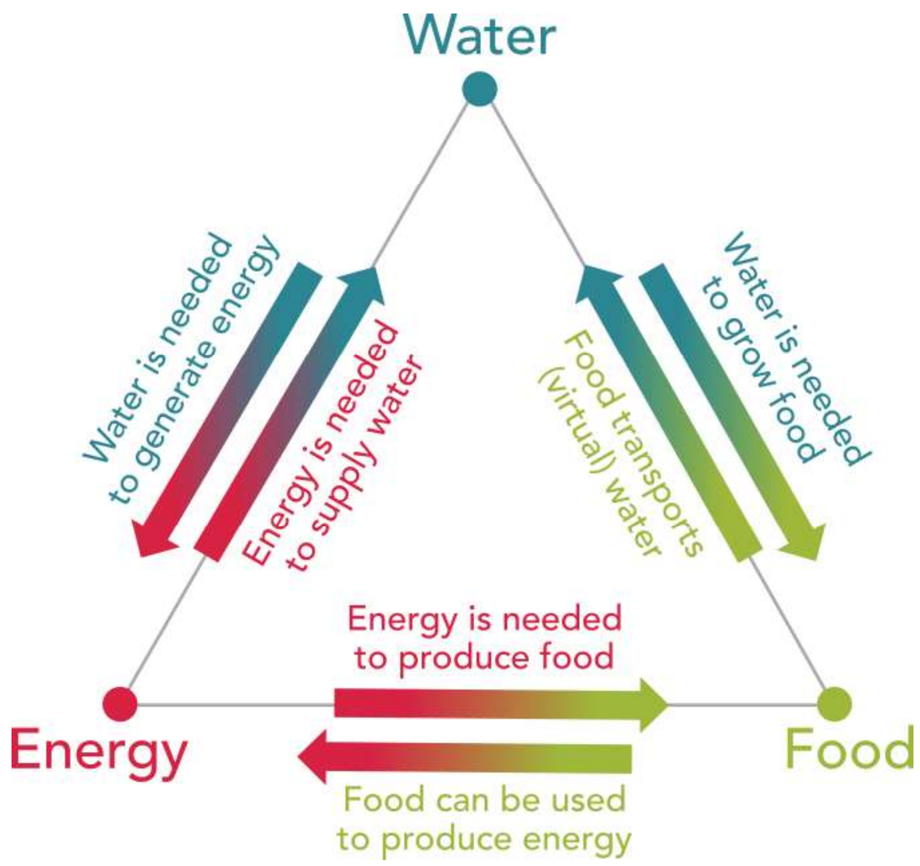


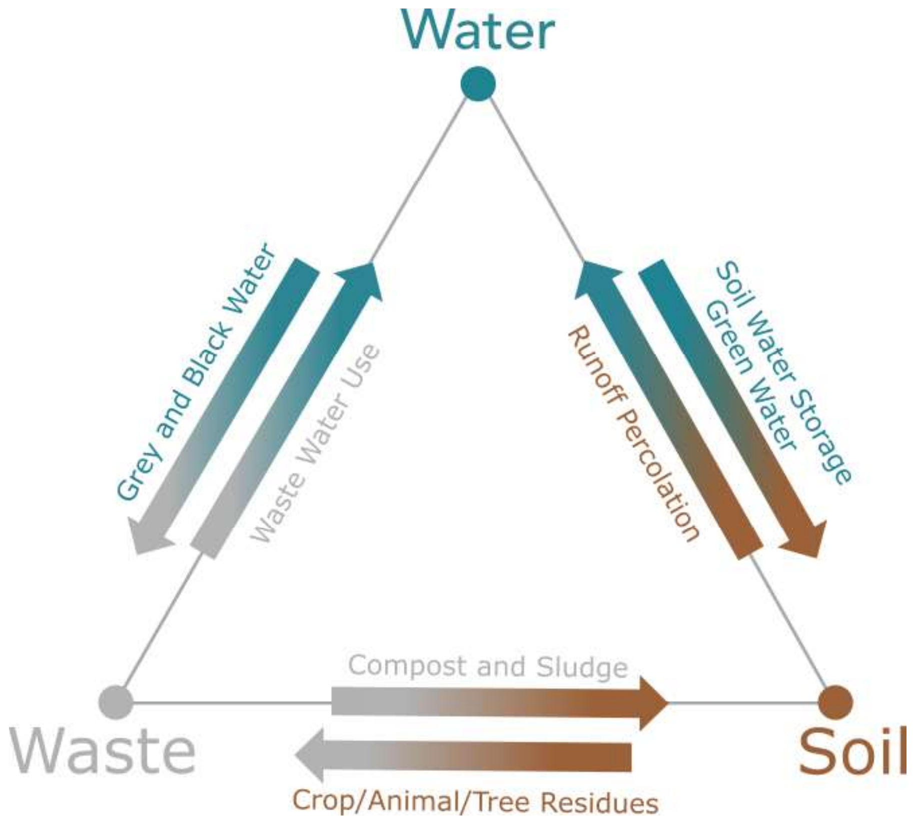
Introduction

WEF Nexus



Source: UNU-FLORES

WSW Nexus



Source: Adapted from Lal (2013)

Lal, Rattan. 2013. ‘Climate-Strategic Agriculture and the Water-Soil-Waste Nexus’. *Journal of Plant Nutrition and Soil Science* 176 (4): 479–93.

Objective

1. Which integrated approaches tackle Water, Soil and Waste ?
2. What has to be integrated within these approaches?
3. Which models are most frequently used within these approaches?
4. How do these approaches simulate integration?

→ **Describe a short vision for integrated modelling under the Water-Soil-Waste Nexus in 2050**

Method

Bibliometrics

"… the application of quantitative analysis and statistics to publications…"

(Thomson and Reuters)

FULL TEXT SEARCH
remove faulty publications
faulty **adequate**
exclude

CATEGORIZATION
assign model to approach if ≥90% of publications refer to it
<90% **≥90%**
"mixed"

RANKING
rank models according to retrieved publications
other **top models**

ANALYSIS

Search syntax

("model abbrev." OR "full name") AND ("approach abbrev." OR "full name")
e.g. ("SWAT" OR "Soil Water Assessment Tool") AND ("IWRM" OR "Integrated Water Resources Management").

Results
1. Integrated Approaches

Integrated Water Resources Management (IWRM)

“Management of water, land and related resources” (Global Water Partnership 2000, 22)

Integrated Solid Waste Management (ISWM)

Combine waste streams, collection, treatment and disposal methods. (McDougall et al. 2001)

Integrated Natural Resources Management (INRM)

Agricultural research to incorporate multiple aspects of natural resource use. (Sayer & Campbell 2003)

Similarities

Developed in the 20th century
Criticise reductionistic concepts

→

Coined in the 1990s
Promote holistic concepts

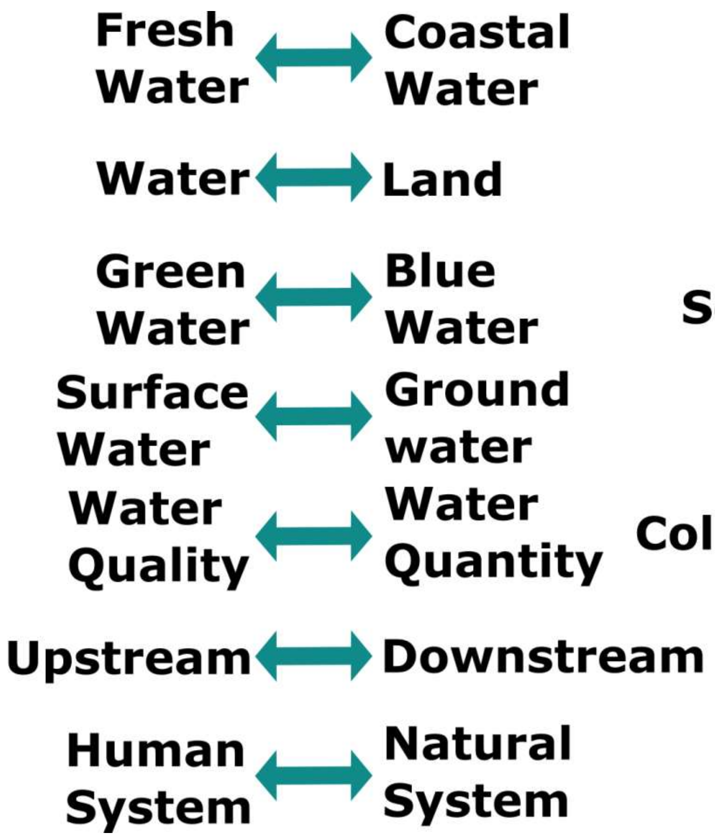
GWP. 2000. *Integrated Water Resources Management*. Stockholm: Global Water Partnership.

McDougall, F. R., P. White, M. Franke, and P. Hindle, eds. 2001. Integrated Solid Waste Management: A Life Cycle Inventory. 2nd ed. Oxford: Blackwell Science.

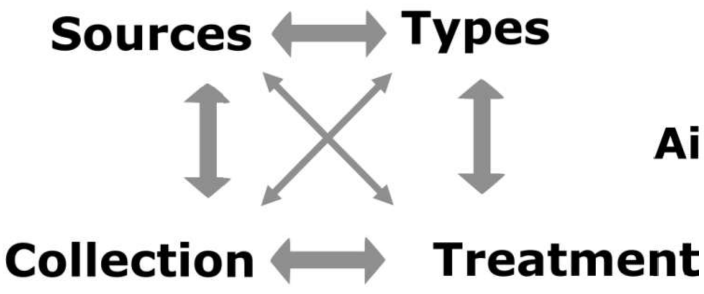
Sayer, Jeffrey, and Bruce Campbell. 2003. ‘Research to Integrate Productivity Enhancement, Environmental Protection, and Human Development’. In Integrated Natural Resource Management: Linking Productivity, the Environment, and Development, edited by Bruce Campbell and Jeffrey Sayer, 1–14. CABI Pub.

Results
2. Integration

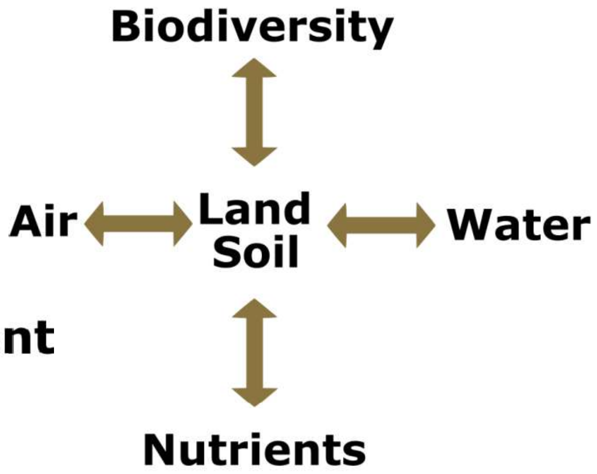
IWRM



ISWM

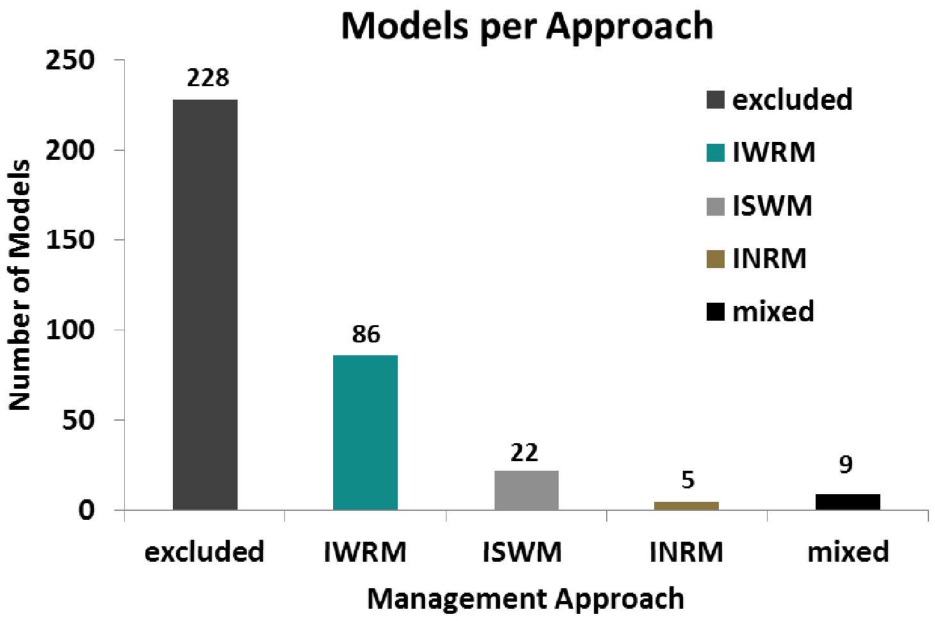


INRM

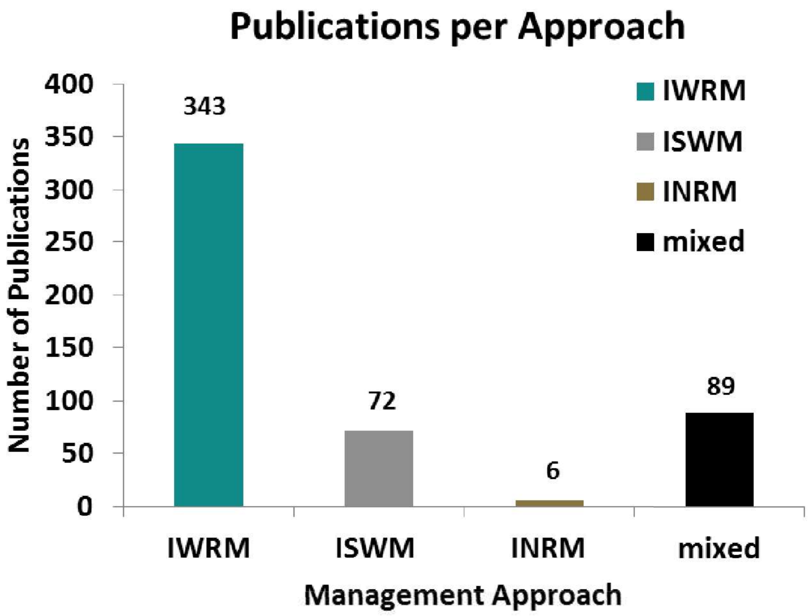


Results
3. Models

350 Models

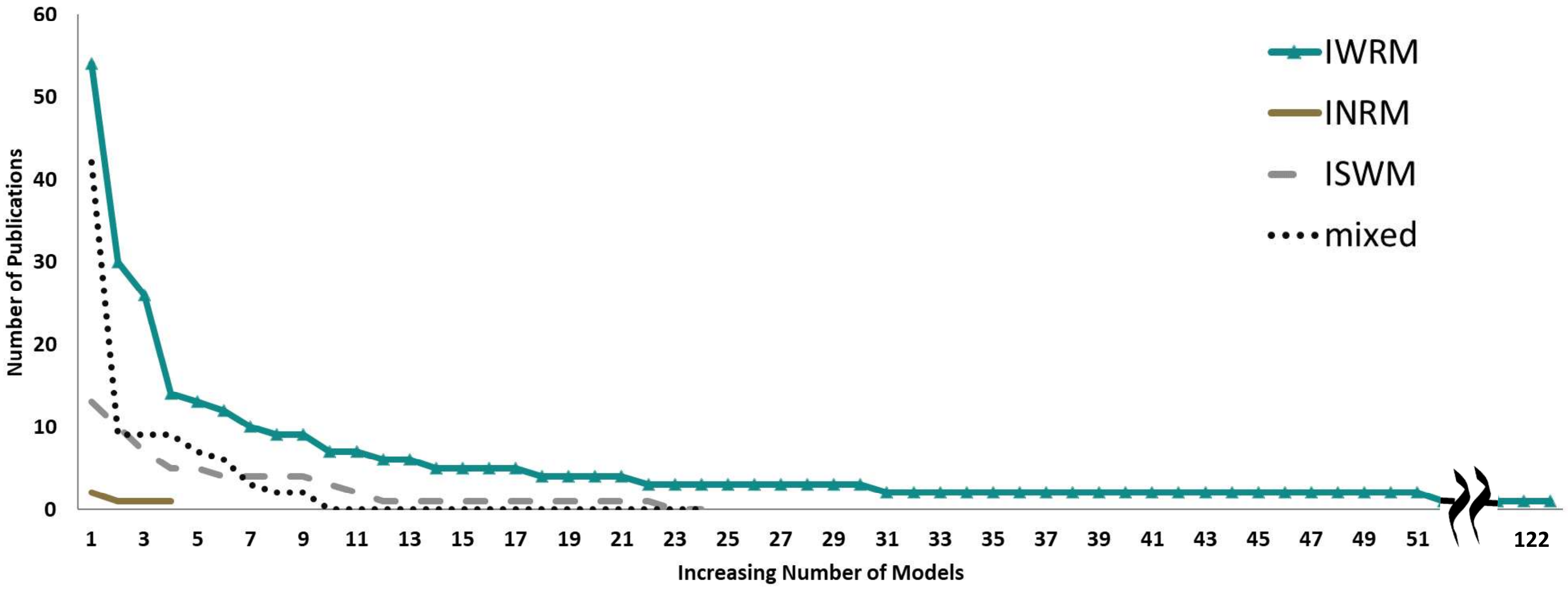


510 Publications



Results
3. Models

Rank	IWRM	Publications	ISWM	Publications
1	SWAT	54	SimaPro	13
2	WEAP	30	ORWARE	10
3	Modflow	26	EASETECH	7
4	ACRU	14	IWM-2	5
5	CROPWAT	13	WRATE	5



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Results
3. Models

Integration	SWAT	WEAP	MODFLOW	ACRU	CROPWAT
Fresh and Coastal Water	-	-	1	-	-
Water and Land	11	4	3	4	1
Surface and Ground Water	1	1	1	-	-
Green and Blue Water	1	2	-	-	3
Water Quality and Quantity	2	4	-	-	-
Upstream and Downstream	2	2	2	-	-
Human and Natural System	1	8	2	-	-

High	Medium	Low	None

Results
3. Models

Integration	ORWARE	EASETECH	WRATE	IWM-2
Sources	🟨 3	🟨 3	⬜ -	🟧 1
Types	🟩 17	⬜ -	🟩 11	🟩 10
Collection	🟨 3	🟨 3	🟨 3	🟨 3
Treatment	🟩 10	🟩 13	🟩 12	🟨 6

🟩 High 🟨 Medium 🟧 Low ⬜ None

Conclusion

How will environmental systems analysis inform the Water-Soil-Waste Nexus in 2050 to support Sustainable Development?

By synergistically increasing holistic and reductionist knowledge.

With modest Nexus models focusing on key interlinkages.

With WSW Nexus specific indicators.

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Thank you for your attention!

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8.4 Publication 4

Learning from Integrated Management Approaches to implement the Nexus

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Review

Learning from integrated management approaches to implement the Nexus

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Holism
Sustainable development
Water-energy-food Nexus
Water-soil-waste Nexus
Integrated resources management
IWRM
ISWM
INRM
Integration

ABSTRACT

In the 1990s, the emergence of Integrated Management Approaches to water, land and waste established a widely accepted understanding on integration of environmental systems. Nexus Approaches try to often build on these. This paper assesses i) the intended goals and features of three Integrated Management Approaches (Integrated Natural Resources Management - INRM, Integrated Water Resources Management - IWRM and Integrated Solid Waste Management - ISWM) and two Nexus Approaches (Water-Energy-Food (WEF) Nexus and Water-Soil-Waste (WSW) Nexus), and ii) how target systems and their integration are viewed in each of the Integrated Management Approaches. From this we assess commonalities and some lessons-learned for the Nexus. The method is based on a systematic literature review and a document analysis. From 1652 articles 52 peer reviewed papers were analysed. The results show that in terms of goals the Nexus Approaches are very similar to Integrated Management Approaches with the addition of clearly wanting to address governance and policy aspects e.g. in the WEF Nexus. Nexus Approaches try to move away from a single-resource centric view (e.g. WSW Nexus) and intend to go beyond resources towards sectors (e.g. WEF Nexus). It cannot be confirmed, that integration is clearly addressed in the analysed Integrated Management Approaches and what integration means is hardly defined. To provide some clarity for Nexus Approaches we propose a concept to describe integration by using "*categories of integration*" and the term "*aspect*" which includes systems, subsystems and other aspects alike.

1. Introduction

After two decades of applying Integrated Management Approaches to water, land and waste the question about their impact remains. Biswas (2008) for instance claims that in the 20th century many approaches have come and gone without leaving anything behind that tells us how we can efficiently manage natural resources in an integrated way. Shortcomings, such as a vague conceptual description or difficulties in implementation, were formulated by Wichelns (2017) for Integrated Water Resources Management (IWRM) and Integrated Natural Resources Management (INRM).

Nonetheless, an even further increased degree of integration emerges. Sectors and resources e.g. in the field of water, energy, agriculture and others are strongly interlinked and complex and so is their management (Hoff, 2011). This is an issue that is relevant in the process and progress towards the Sustainable Development Goals (SDGs) as the manifold goals are interlinked themselves; progressing in one goal may result in either synergies or trade-offs between them (ICSU, 2017). To advance integrated management and account for these issues, the notion of the Nexus entered the debate on Sustainable Development in recent years (Kurian, 2017).

While defining Nexus Approaches to land, water and waste, learning from Integrated Management Approaches that have dealt with each of the resources separately in the past is considered a critical stepping stone in providing functional solution options. Therefore, this paper assesses i) the intended goals and features of the three integrated approaches (Integrated Natural Resources Management - INRM, Integrated Water Resources Management - IWRM and Integrated Solid Waste Management - ISWM) and contrasts them with the ones set by the Water-Energy-Food (WEF) Nexus and the Water-Soil-Waste (WSW) Nexus, and ii) how target systems and their integration are viewed in each of the Integrated Management Approaches.

Before proceeding, the two Nexus approaches and the three Integrated Management Approaches shall briefly be introduced.

1.1. The Nexus notion

The Nexus aims to shift from integration *within* sectors to integration *between* sectors or resources. The Water-Energy-Food (WEF) Nexus, for instance, recognizes that the water-, food-, and energy sectors depend on each other (Hoff, 2011). The WEF Nexus aims to support a transition to a green economy in two ways: achievement of greater policy coherence and higher resource efficiency (Hoff, 2011). By cutting down trade-offs and creating synergies, the WEF Nexus' objectives

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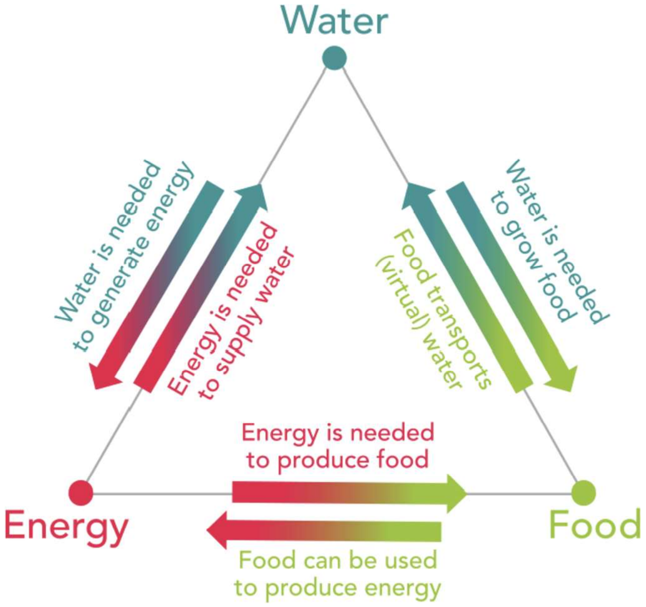

Fig. 1. Interactions within the WEF Nexus.
Source: UNU-FLORES.

are also increasing the security of water, energy, and food (Hoff, 2011). A generally accepted definition of the WEF Nexus has not come up yet. Nonetheless, Hoff's background paper (2011) prepared for the Bonn 2011 Nexus conference significantly influenced shaping of the approach. From his perspective, the WEF Nexus can be understood under the context of achieving water-, energy, and food security in a rising green economy. Fig. 1 shows some examples of the interactions between the three sectors.

While the WEF Nexus is about sectors, the Water-Soil-Waste (WSW) Nexus considers resources. In order to support food security, for instance, the WSW Nexus does not tackle the food sector. It would rather aim to look at important resources needed to produce food and hence, focus on the interactions between water and soil (UNU-FLORES n.d.a). Fig. 2 shows some of the interlinkages of the WSW Nexus resources as described in R. Lal (2013).

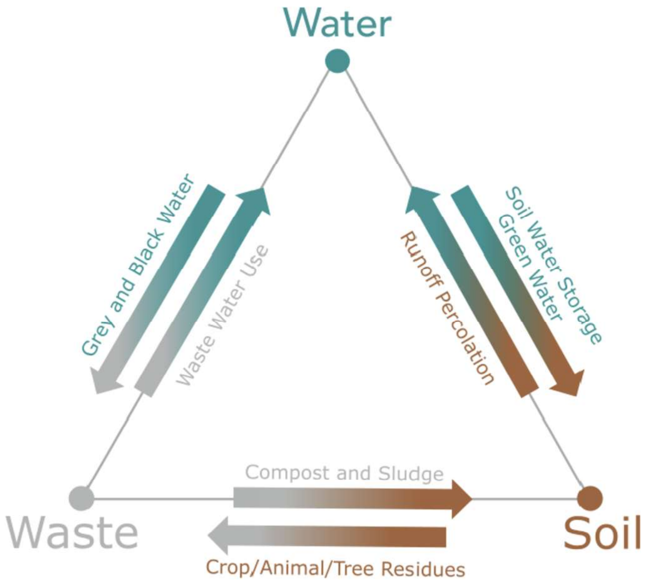

Fig. 2. Interlinkages within the WSW Nexus.
Source: Design adapted from UNU-FLORESContent based on R. Lal (2013).

UNU-FLORES describes the WSW Nexus as an

> "*[a]pproach to environmental resources' management [that] examines the inter-relatedness and interdependencies of environmental resources and their transitions and fluxes across spatial scales and between compartments. Instead of just looking at individual components, the functioning, productivity, and management of a complex system is taken into consideration.*" (UNU-FLORES n.d.a, paragraph 1).

The Nexus described at UNU-FLORES explicitly considers waste as a resource (Schwärzel et al., 2014). In food production waste may play a role when considering wastewater for irrigation or nutrients from wastewater for fertilizing (R. Lal, 2013). As part of the Nexus notion, the WSW Nexus aims to tackle interlinkages between the resources soil, water and waste to reveal trade-offs and synergies. Based on this the WSW Nexus supports environmental decision-making within different boundaries of these resources systems (Avellán et al., 2017).

1.2. *Integrated management of water, soil and waste*

Water resources professionals who are used to systems analysis put forward Integrated Water Resources Management (IWRM) (Allouche, 2016) as a systems approach to the study of water resources (Wichelns, 2017) and an interdisciplinary and holistic manner of managing them. The Global Water Partnership (GWP) states that IWRM is

> "*a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems.*" (GWP, 2000, 22).

Nowadays, IWRM is a dominant and widely acknowledged paradigm of water management (Jeffrey and Gearey, 2006; Petit, 2016; Crase et al., 2018). Despite ongoing criticisms and controversial discussion, the goal to implement IWRM throughout the globe continues. The commitment of SDG 6.5 to IWRM portrays that it is high on the agenda in today's water resources management (United Nations, 2015).

Integrated Natural Resources Management (INRM) as described by the Consortium of International Agricultural Research Centers (CGIAR) is based on a systems approach that strives to impact the quantity and quality of natural resources related to agricultural activities. INRM was stimulated by shortcomings in the agricultural sector during and after the time of the green revolution (after the 1970s) in combination with an increasing understanding of the role of ecosystems (Izac and Sanchez, 2001, CGIAR, 2000). A common definition comes from the CGIAR which defined INRM in 2000 as:

> " *a conscious process of incorporating multiple aspects of natural resource use into a system of sustainable management to meet explicit production goals of farmers and other uses (*e.g.*, profitability, risk reduction) as well as goals of the wider community (sustainability).*" (CGIAR, 2000, 5).

Before the 19th century waste management was a simple disposal of waste within or outside the cities (Marshall and Farahbakhsh, 2013). McDougall et al. (2001) base Integrated Solid Waste Management (ISWM) on the concept of sustainability. Thus, waste management must incorporate the economic, environmental and social dimensions. The idea is that many options of waste management in collecting, transporting, treating and disposing waste, should not only be considered in simple comparisons, but also be carefully analysed in accordance to an approach that can better economic and ecological efficiency through systemic and scientific approaches (Abounajm and Elfadel, 2004). A definition of Integrated Waste Management is given by McDougall et al. (2001) in the well-known book *Integrated Solid Waste Management*:

> "*Integrated Waste Management systems combine waste streams, waste collection, treatment and disposal methods, with the objective of achieving environmental benefits, economic optimisation and societal*

acceptability. This will lead to a practical waste management system for a specific region" (McDougall et al., 2001, 15).

2. Methods

To answer the research questions, the study applies both a systematic literature review and a document analysis.

2.1. Assessing intended goals and features

The intended goals and features of the approaches (Results in section 3.1.) were analysed through a systematic literature review.

In our understanding, *goals* describe the aim or results pursued by an approach. A further commonality that the approaches share is that they provide *elements*, *features* and *characteristics*. McDougall et al. (2001) describe the *characteristic* of INRM, while Sayer and Campbell (2003) outline the *key features* of INRM. This article will use the term *features* for all such *elements* or *characteristics* that make up an approach in order to achieve its goals. While goals are the end the approaches seek, the features are the means to that end.

A five step review process, was carried out. Literature is first identified, selected, appraised, then information is collected and analysed (see Fig. 3).

For identification, the literature review is conducted for peer reviewed articles from the years 1990–2017. The databases of ScienceDirect and Web of Knowledge are searched for the full name or the abbreviation of the approaches in keywords, title and abstract.

To select the most relevant articles the vast amount of articles must be reduced in several subsequent steps. The duplicates in the articles between the two databases are removed. Then unrelated articles are sorted out by scanning titles and abstracts. Unrelated articles do not cover the topic of the approaches whatsoever, ISWM e.g. means *Inter Scale Wavelet Maximum* in biomedical engineering (Arikidis et al., 2002).

In the appraisal step, the remaining articles are separated into *conceptual* and *non-conceptual* articles. The separation is done upon the judgement of the authors after reading the titles, and if necessary abstracts. Conceptual in this sense refers to articles that discuss the approaches on a general basis including their history, goals, features and criticism. An article is considered *non-conceptual* when it refers to specific aspects of the approach (e.g. *groundwater-surface water interactions in wetlands for integrated water resources management*) or with a focus on a specific region (e.g. *integrated water resources management for Egypt*). Non-conceptual articles also include methodological and empirical articles as well as case studies. The conceptual papers are then ranked by the citations indicated in the Web of Knowledge database. For each approach, the ten articles with the highest citations are picked. To also include more recent articles that may have not been cited as often as older papers, the conceptual articles of 2016 and 2017 are additionally checked and chosen if deemed relevant. This is done regardless of the citations they received. Thus, for each of the scrutinized approaches at least ten and maximum 14 articles are chosen to be analysed. Table 1 shows an overview of the search criteria as well as the number of articles found during the literature search and chosen in the subsequent steps.

It must be noted that the WSW Nexus receives very little attention in the two scholarly databases (three articles in April 2017!). Therefore, a slightly different approach is chosen. The literature published by UNU-FLORES in the recent years is checked for conceptual writings. Altogether six relevant publications are chosen and analysed. Due to this difference in selecting these articles, the procedure is not shown in the table.

In total, this literature review consists of 52 articles.

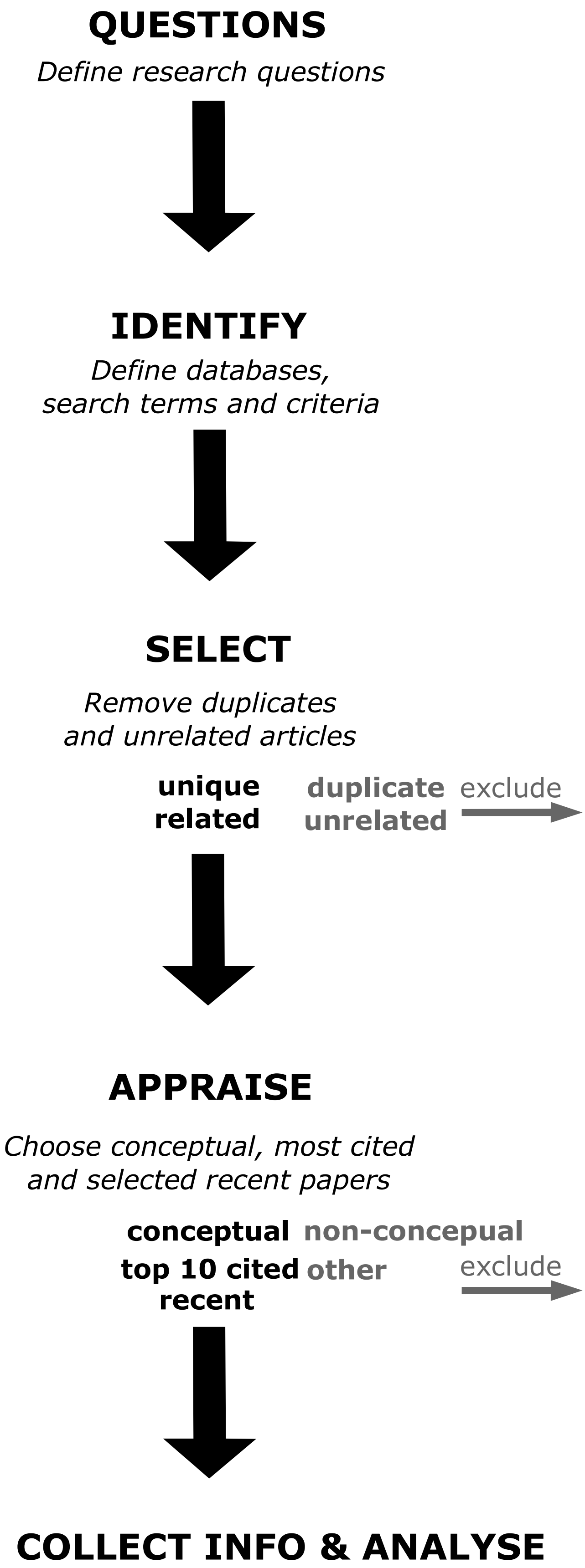

Fig. 3. Literature review flow chart.

2.2. Determining target systems of and integration in integrated management approaches

The target systems of and integration in Integrated Management

Table 1
Overview of the literature search method.

Applicable to all approaches					
Databases and time of search	*Science Direct | Web of Knowledge | Time of search: April 2017*				
Search term	*'Abbreviation' OR 'full name'* (e.g. *'INRM' OR 'integrated natural resources management'*)				
Search Criteria	*Years: 1990 – 2017 | Publications: Journal Articles | Search in: Title, Abstract, Keywords*				
	ISWM	***INRM***	***IWRM***	*WEF Nexus*	***Total***
Total articles found	*173*	*76*	*1223*	*180*	*1652*
Duplicates	*50*	*11*	*210*	*42*	*313*
Unrelated articles	*8*	*24*	*-*	*-*	*32*
Non-conceptual articles	*104*	*39*	*933*		*1076*
Conceptual articles	*10*	*20*	*80*	*28*	*138*
Chosen articles with highest citations	*10*	*10*	*10*	*10*	*40*
Range of citations of chosen articles	*148–1*	*46–6*	*272–44*	*73–4*	*-*
Additional chosen articles 16/17	*-*	*1*	*1*	*4*	*6*
Total number of chosen articles	*10*	*11*	*11*	*14*	*46*

Approaches (Results in section 3.2) were analysed through the analysis of key documents with outstanding importance to the respective approach. The chosen method for this part is a *document analysis*. "Document analysis is a systematic procedure for reviewing or evaluating documents" (Bowen, 2009, 27). It is a qualitative research method to produce knowledge through structured examination and interpretation of text and other included means of information, such as figures (Bowen, 2009).

A key document in this article refers to a publication which had a major influence on the chosen integrated approach. It is preferably a book which contains the definition of the approach, is published by a major institution advocating for the approach and is often cited within the literature analysed in the 52 articles chosen for the literature review.

For IWRM, the Background Paper Nr. 4 *Integrated Water Resources Management* published by GWP (2000) is used. For INRM, the book *Integrated Natural Resources Management* by Sayer and Campbell (2003) is analysed. For ISWM the book *Integrated Solid Waste Management – a Life Cycle Inventory* (2nd edition) by McDougall et al. (2001) is chosen.

We understand a *target system* as the environmental system that is the main focus of each of the approaches, i.e. the water system in IWRM. A system can be defined as "a set of interconnected parts which function together as a complex whole" (Smithson et al., 2008, 9). A system is characterized by processes (e.g. fluxes), stores (e.g. a soil profile) and subsystems (e.g. groundwater in the hydrological cycle) (Smithson et al., 2008). In this article, this definition is also applied to the waste sector, where for instance the treatment of solid waste is a subsystem of the waste system. Smithson et al. (2008) point out that systems analysis is a methodology for investigating complex systems and define it as "… [t]he study of systems, for example hydrological systems, atmospheric systems and ecosystems in physical geography." (p. 752).

In this study, we assume that an approach aims to integrate the target system with its related targets to also eventually understand which interlinkages are important for modelling.

3. Results

3.1. Intended goals and features of integrated management approaches

3.1.1. Intended goals

The analysis shows that one goal that all approaches have in common is to achieve sustainability within their field of management (see Table 2). Other goals that are similar among the approaches are to consider and synergize various, also conflicting interests and views; this is the case especially in INRM and IWRM.

3.1.2. Features

The literature analysis of the five approaches (ISWM, INRM, IWRM, WEF Nexus, WSW Nexus) yielded around 30 different but related

Table 2
Overview of goals described in the literature for each approach.

Integrated Approaches	*Goals*	*Source*
INRM	● Enhance agricultural productivity in a sustainable manner ● Reconcile, consider and synergize various (conflicting) interests ● Integrate the human and the natural system	(Izac and Sanchez, 2001), (Merrey et al., 2005), (Frost et al., 2006), (Walker et al., 2001), (Dalsgaard and Oficial, 1997), (Hagmann et al., 2003), (Twomlow et al., 2008), (van Oosterzee, Dale, and Preece, 2014)
ISWM	● Combination of waste management options in a sustainable manner ● Maintenance or increase of public health and quality of life ● Protection of the environment ● Reduction, Reuse, Recycling/Recovery of waste ● Integration of waste materials, sources of waste, treatment methods, processes, technologies, sectors and stages	(Clift et al., 2000), (Wilson et al., 2012), (Marshall and Farahbakhsh, 2013), (Solano et al., 2002) (Huang et al., 2005), (Menikpura et al., 2013), (Levis et al., 2013), (Memon, 2010), (Abdoli et al., 2016)
IWRM	● Manage water, land and related resources in a sustainable manner ● Provide ecosystem solutions ● Balance various (conflicting) interests ● Integrate the human and the natural system	(Biswas, 2004), (Biswas, 2008), (Medema et al., 2008), (Jonker, 2002), (Jeffrey and Gearey, 2006), (Jønch-Clausen and Fugl, 2001), (Grigg, 2008), (McDonnell, 2008), (Savenije and Van der Zaag, 2008)
WEF Nexus	● Achieve water-, energy- and food security ● Support Sustainable Development and the SDGs ● Increase resource efficiency and optimization ● Inform resource governance and promote rational decision-making ● Enhance policy coherence and cooperation within and between sectors ● Shift from integration within the sector to cross-sectoral integration	(Smajgl et al., 2016), (Lawford et al., 2013), (Biggs et al., 2015), (Muller, 2015), (Leck et al., 2015), (Endo et al., 2015), (Wong, 2014), (Machell et al., 2015), (Rasul and Sharma, 2016), (Kurian, 2017), (Wichelns, 2017), (Al-Saidi and Elagib, 2017)
WSW Nexus	● Ensure human well-being and health ● Sustainable management of water, soil and waste ● Increase resource efficiency and optimization	(Schwärzel et al., 2014), (Kurian and Ardakanian, 2015), (Alcamo, 2015), (Herath, 2014)

Table 3
Summary of features of Integrated Management Approaches and the Nexus.

Features	*ISWM*	*INRM*	*IWRM*	*WEF Nexus*	*WSW Nexus*
Reform governance arrangements			*X*		
Strengthen legislation and policy	*X*				
Community-based activities and governance		*X*			
Consider governance, norms, institutions, organisations				*X*	*X*
Holism	*X*	*X*	*X*	*X*	
Systems Approach	*X*	*X*	*X*	*X*	*X*
Participation and inclusion of stakeholders	*X*	*X*	*X*	*X*	*X*
Embrace complexity	*X*	*X*	*X*		*X*
Embrace uncertainty		*X*	*X*		
Interdisciplinary	*X*	*X*	*X*	*X*	*X*
Transdisciplinary		*X*	*X*	*X*	*X*
Consideration of local context	*X*	*X*			
Aim for local impact	*X*	*X*			
Research paradigm		*X*			
Increase adaptive capacity		*X*			
Based on efficiency and equity			*X*		*X*
People-centred		*X*			
Bring together sectors				*X*	
Focus on the poor				*X*	
Multiple scales of analysis and scaling up and out		*X*			
Consider different scales					*X*
Reduce trade-offs and increase synergies				*X*	*X*
Focus on systems efficiency				*X*	
Promote partnering private sector to improve Nexus-based investments				*X*	
Provide methods and tools for assessment				*X*	
Combine different modelling approaches					*X*
Economic incentives			*X*		*X*

features that are summarized in Table 3. The features of the approaches are in some parts different but are also very similar in other cases. Especially the aim for a holistic management, to apply a systems approach and thus, also embrace complexity is a common feature to almost all approaches. Moreover, to include stakeholders and ensure participation as well as to tackle issues in an interdisciplinary and/or transdisciplinary manner are statements that are frequently found in literature on the approaches. Other aspects such as to reduce trade-offs and increase synergies or to enhance overall system efficiency receive increased attention especially within the Nexus.

3.2. *Target systems of and integration in integrated management approaches*

3.2.1. *Target systems*

Each approach has its own target systems as shown in Fig. 5 and also describes them in different ways. For example the definition of the target systems for INRM is not straightforward. The document under analysis does not mention explicitly which systems are in the focus of INRM. Neither the name of the approach nor the definition of INRM clarifies this question more detailed than speaking of *natural resources*. The definition of INRM aims at "incorporating the multiple aspects of natural resources" but also puts a focus on the "explicit production goals of farmer" (CGIAR, 2000, 5). Even though it is not the only resource a farmer is concerned about, it is intuitive that soil fertility belongs to a farmer's main concerns. Further related targets to INRM are biodiversity, water, nutrients and air (CGIAR, 2000; Campbell et al., 2003; Sayer and Campbell, 2003).

For ISWM the target system is the solid waste system. This includes the collection of waste as well as its treatment, recycling and disposal (McDougall et al., 2001). The waste system does not include interlinkages with environmental systems or natural resources outside its own system. Fig. 4 from McDougall et al. (2001) underlines this. Here, the waste system is within societal boundaries. ISWM does not investigate the interlinkages with the environment neither at the input side with natural resources nor at the output side with pollution. Inputs in form of energy and raw materials and outputs as emission are considered; however, not as interlinkages from, or to the environment.

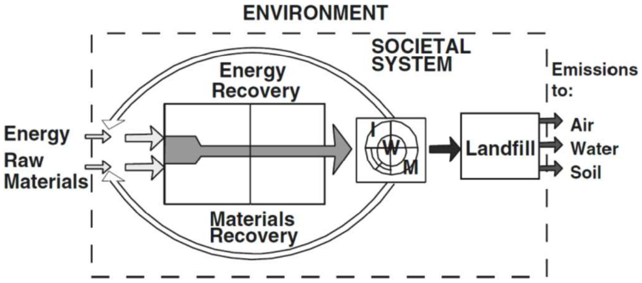

Fig. 4. Integrated Waste Management within the societal system.
Source: McDougall et al. (2001).

The target system of IWRM is the water system as derived from the hydrological cycle (GWP, 2000). In the IWRM definition by GWP (2000) it is additionally mentioned that "land and related resources" and their interaction with water are also considered (p. 22). Thus, they are related targets of the IWRM approach. However, it is not further defined what these related resources are.

In summary, in INRM, soil/land is the target, while air, nutrients, water and biodiversity are related targets. In ISWM, waste is the target system. In IWRM it is water that is the main target system while land and other resources are related targets.

3.2.2. *Integration*

Fig. 6 shows a schematic summary of the categories of integration with regard to the examined approaches. In INRM it is always land/soil which has to be integrated with biodiversity, air, nutrients and water. In IWRM seven very different categories of integration exist, while ISWM focuses on the integration across waste sources, types, treatment and collection.

The question of integration is not prominently featured in INRM. What has to be integrated is not described in the INRM literature. Therefore, it must be concluded that the INRM target system (land/soil) has to be integrated with its related targets.

Integration in the approaches refers to much more than integrating different natural components. Sayer and Campbell (2003) make this clear when they summarize the work of P. Lal (2001) stating that INRM is about integration across different stakeholders, disciplines, scales and components. The integration of natural components is rarely addressed in the studied literature and not as prominently featured as expected.

The above statement to *integrate across components* is not further explained. The term 'components' implies *natural components*. From this it is concluded that the target system of INRM (soil/land) and its related targets (air, water, biodiversity and nutrients) are meant, which then have to be integrated with each other.

Fig. 5. Target systems and related targets of INRM (left), ISWM (centre) and IWRM (right).

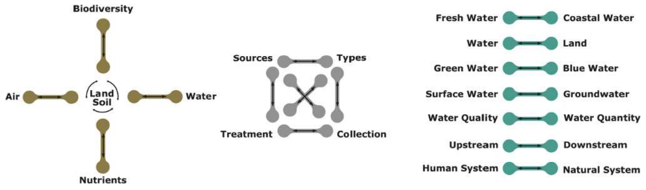

Fig. 6. Integration within INRM (left), ISWM (centre) and IWRM (right).

Van Noordwijk et al. (2003) address the question of integration in INRM. When they speak of integration they exemplarily refer to agroforestry where the interactions of trees, soils, crops and animals as landscape elements lead to environmental services. This implies, in addition to the integration *between* components, also the integration *within* the target system soil/land. In agroforestry, different land uses and soil are integrated. The integration within the soil/land system is not further specified here. Thus, it is concluded that in INRM integration occurs within the target systems and also between the target systems and its related targets (see Fig. 6). One must keep in mind that it is not the INRM approach that states that its target system and related targets are also the aspects of integration. This is the interpretation that is done in this article, based on the information from the literature.

For integrated waste management all integration lies within the waste system because ISWM does not have any related targets. First, a waste system must be integrated in all solid waste materials, not only already recyclable and profitable types of waste (McDougall et al., 2001). Second, all sources of solid waste must be integrated reaching beyond the municipal sources to commercial, industrial, construction or agricultural waste. A waste management is likely to be more effective if the same waste type of several sources can be combined (McDougall et al., 2001). Third, the system must be integrated in different collection methods (e.g. curb side collection) (McDougall et al., 2001). Fourth, is the integration of several treatment methods that may be combined in relation to the context to reach an effective waste management system. This can include the integration of anaerobic digestion, composting, energy recovery, recycling or landfilling (McDougall et al., 2001).

Thus, the interlinkages in a waste system are manifold. Within a waste system "all processes and technically feasible combinations of processes need to be possible." (McDougall et al., 2001, 113). Derived from the above descriptions, integration in solid waste management must consider i) interlinkages between all types and sources of waste with, ii) feasible combinations of collection and treatment. Within the scope of this article, interlinkages that fall within this definition are considered relevant for modelling within the ISWM approach. A category of integration therefore includes one of the four aspects and its interlinkages to the other three (see Fig. 6).

The question of what has to be integrated in IWRM is clearly stated. GWP (2000) dedicates a subchapter to this question. Several interactions within the natural system (e.g. water and land) and the human system (e.g. cross sectoral integration in national policy) have to be integrated in IWRM. Hereby the focus is on the integration of the natural system, where IWRM aims to integrate seven interactions described in GWP (2000) or Jønch-Clausen and Fugl (2001). These seven interactions are between i) fresh water and coastal water management, ii) land and water management, iii) green water and blue water, iv) surface water and groundwater management, v) upstream and downstream interests, vi) water quantity and quality and vii) water and wastewater management (see Fig. 6).

4. Discussion

This paper assessed i) the intended goals and features of three integrated approaches (Integrated Natural Resources Management - INRM, Integrated Water Resources Management - IWRM and Integrated Solid Waste Management - ISWM) and two Nexus Approaches (Water-Energy-Food (WEF) Nexus and Water-Soil-Waste (WSW) Nexus), and ii) how target systems and their integration are viewed in each of the Integrated Management Approaches.

A goal that all approaches, including the Nexus Approaches, have in common is to achieve sustainability or support sustainable development. Other common goals among the approaches are to consider and synergize various, also conflicting (for the case of IWRM), interests. The approaches embrace complexity. While the WSW Nexus maintains a resource management perspective that is very similar in its goals to the Integrated Management Approaches, the WEF Nexus adds an explicit goal towards policy coherence and informed decision making that includes governance aspects.

When assessing the features, Integrated Management Approaches seem to have largely moved away from purely reductionist and engineering-based approaches towards a more holistic view in managing environmental resources. All approaches, including the Nexus, apply systems analysis to embrace the complexity that a holistic view entails.

The terms *reductionism* and *holism* seem to be so well known that none of the investigated literature goes more into detail on what these terms exactly mean. As they are an important common feature of all approaches the terms will be described on the example of agriculture based on Jordan (2013) in his writing on *Holism vs. Reductionism in Environmental Science.*

"Holism is looking at the properties of a system in its entirety, […]. Reductionism is looking at mechanisms that influence these properties" (Jordan (2013), 217). When observing changes in a system, the question that reductionistic science asks is "[w]hat is the mechanism that causes this effect?" (Jordan (2013), 221). Hence, reductionism aims to understand a mechanism or process but without taking into account how this influences the dynamic of the entire system. Holistic view is capable of setting processes into context with each other with the possibility to increase the effectiveness of the entire system rather than one process. This is in line with Jordan (2013) when he states that "… [h]olism is necessary for solving management problems" (Jordan (2013), 218). Holism, as understood in this article, takes a step back to a higher level to see the entire system. This is not static and depends on the view. "A physiologist considers cell biology to be reductionistic. A cell biologist considers a molecular biology to be reductionistic"; the other way around the upper level is holistic (Jordan (2013), 218).

In addition, all approaches feature the need for a systems approach, interdisciplinarity and the participation and inclusion of stakeholders. Considerations of trade-offs and synergies are specific to the Nexus Approaches. With respect to considering governance aspects, both Nexus Approaches feature this prominently, but also Integrated Management Approaches allude to it (e.g. for IWRM – Reform governance arrangements). Both ISWM and INRM also emphasize the need for the inclusion of local considerations and making local impact. The Nexus Approaches pick up on these aspects in part by focusing on the poor (WEF) or considering different scales (WSW).

Thus, in terms of goals the Nexus Approaches are very similar to Integrated Management Approaches with the addition of clearly wanting to address governance and policy aspects in the WEF Nexus. When it comes to features, all systems mostly also coincide with wanting to work with and through stakeholders in an inter/transdisciplinary manner while applying a systems approach. Explicit governance considerations as well as trade-offs and synergies are features that distinguish Nexus Approaches, in part, from Integrated Management Approaches.

For the Integrated Management Approaches the target systems are clear for IWRM – water, and IWSM – solid waste, but less so for INRM – land/soil. The systems of the WSW Nexus are that of the resources water, soil and waste (solid or liquid). With the Nexus Approach the relationship between different compartments of Integrated Management Approaches has changed. It is not anymore the management of one resource that takes into account related resources, but rather the relation of each resource to the other without prioritizing one

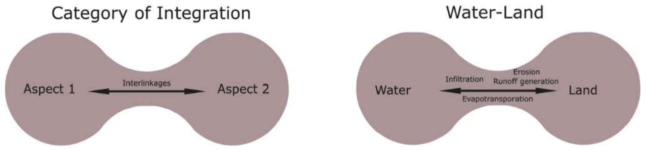

Fig. 7. Concept of the Categories of Integration in theory (left) and as example (right).

over the other. The systems of the WEF Nexus are Water, Energy and Food. In the WEF Nexus, water supply -, energy- and food sectors and their interactions are considered together. Interesting is that Hoff (2011) describes that water still holds a crucial role as variable in producing energy and food. Hence, while placing the sectors of food, water supply and energy in an equal triangle, water as a resource continues playing a central role for the WEF Nexus (Hoff, 2011). In summary, Nexus Approaches try to move away from a single-resource centric view (WSW) and intend to go beyond resources towards sectors (WEF).

It cannot be confirmed, that integration is clearly addressed in the analysed Integrated Management Approaches. Even though very similar in wording integration implies in some cases very different things. That integration is simply between the target systems and their related targets identified in section 3.2.1 was not the case. Examples of integration are wide-ranging, such as integrating policies and programs, integrating different sources of waste or integration between subsystems (groundwater – surface water) and between systems (water – land). Integration is barely addressed conceptually. What integration means is hardly defined in any of the analysed documents. The terms target systems, related targets and integration, were given less emphasis within the examined literature than one might expect. One assumption is that the term(s) belong to a jargon in which everyone is a priori expected to understand its meaning.

In the conclusion we aim at providing some clarity on this for the Nexus Approaches.

5. Conclusion

By looking at past developments of Integrated Management Approaches one can conclude that they have paved the way in favour of the Nexus. Even though, we claim that the term integration lacks description on its definition and operationalization, the emergence of "integrated approaches" in the 1990s established a wide acceptance of managing environmental sectors and resources in an integrated way. This has started *within* each sector and has – with the Nexus – led to integration *across* sectors and resources. Thus, integrated approaches have indirectly influenced the establishment of the WSW Nexus and the awareness that resources must be viewed as interlinked.

Based on what we learned from Integrated Management Approaches we propose to describe integration with the concept of the *category of integration* and the term *aspect* which includes systems, subsystems and other aspects alike (see Fig. 7). Different aspects of an approach have to be integrated. An aspect is defined as "[a] particular part or feature of something" (Oxford Dictionary, 2017, paragraph 1). In this case, *something* would refer to the approach. Examples are the integration of different systems (e.g. water-land), subsystems (e.g. surface water-groundwater) or even other aspects such as waste types-treatment or upstream-downstream.

To grasp this issue, the concept of the *category of integration* is suggested here. Such a category of integration describes the connection between two aspects of the integrated approach. A category may consist of many interlinkages which connect the two aspects. Fig. 7 clarifies this concept theoretically (left) and exemplarily for two aspects of IWRM (right).

For the WEF Nexus integration could thus mean to integrate the categories of i) water for energy, ii) energy for water, iii) water for food and iv) energy for food (see also Fig. 1). Hoff (2011) dedicates a chapter to the "interactions across the Nexus" (p. 18) where he describes the before mentioned four interactions. Therefore, it must be assumed that these are the categories that should be integrated with each other when adopting the Nexus Approach. All three sectors (as categories of integration) are considered in the WEF Nexus and integrated with each other which does not necessarily mean, that there are interlinkages between all categories in all directions.

For the WSW Nexus resource integration could revolve around integrating i) water for soil (moisture) and soil for water (quality or storage), ii) water for waste (dilution/transport), and iii) (organic) waste for soil (amendment), waste (water) for soil (fertilization) and soil for waste (storage).

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8.5 Publication 5

The nexus: concepts and frameworks

T. Avellán, **M. Roidt**

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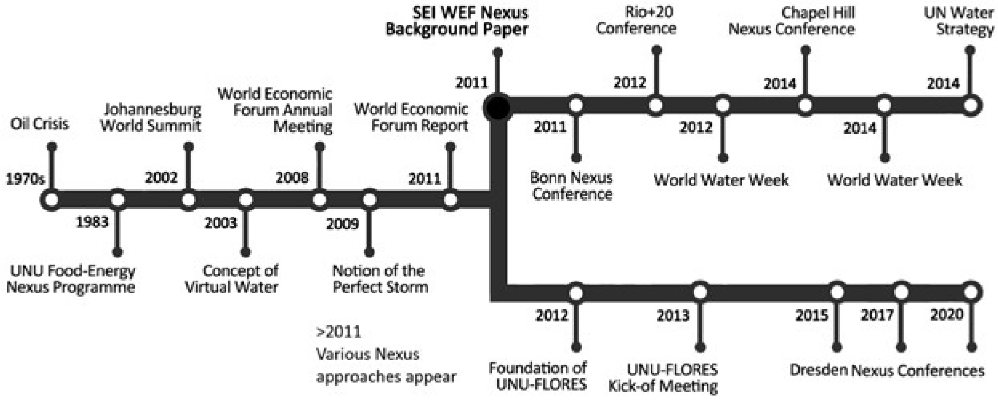
2. The nexus: concepts and frameworks

Tamara Avellán and Mario Roidt

2.1 INTRODUCTION

Knowledge on the interlinkages between different sectors and resources such as water, land, food and energy has always been there. Especially in local settings, nexus-like interlinkages must have long been known. Farmers in irrigated agriculture who stored and developed water resources or craftspeople who developed hydropower over centuries would not be surprised by the nexus notion.

A connection between energy and food, however, appeared in a more general sense when the increasing oil prices during the 1970s suddenly hindered the poor to cook food (Schwärzel et al., 2014). A decade later, the notion of a nexus in the context of food and energy emerged when the United Nations University launched the Food-Energy Nexus Programme (see Figure 2.1 for a timeline). The university developed an analytical framework to tackle food and energy-related challenges (Al-Saidi and Elagib, 2017; Kurian and Ardakanian, 2014, 2015; Schwärzel et al., 2014). Even though the nexus notion had not yet gained ground, the World Summit in Johannesburg in 2002 implicitly recognized the water-energy-food (WEF) nexus by placing water and sanitation, agricultural productivity and energy among its priority areas (Herath, 2014).



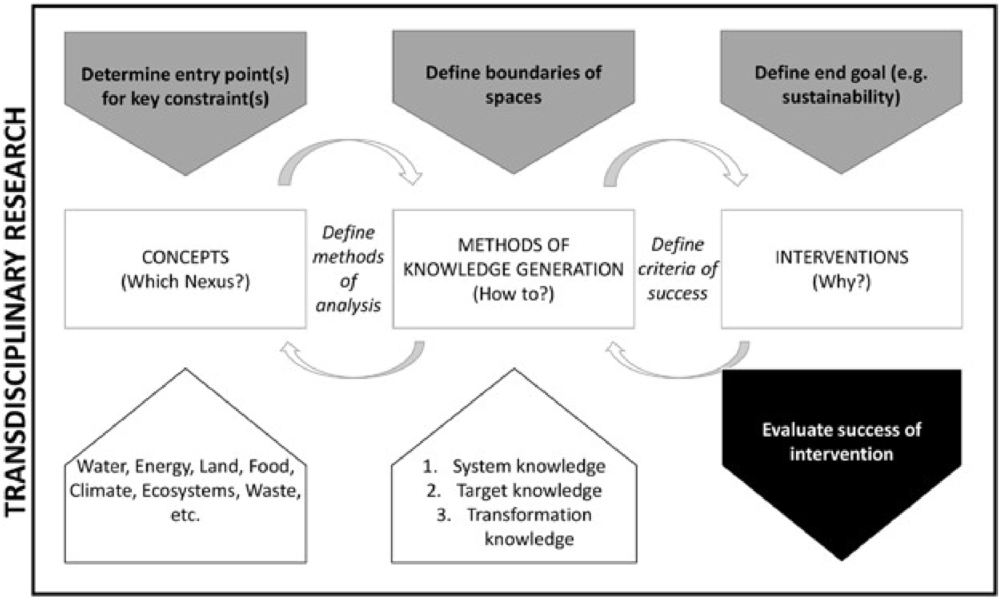
Source: Updated from Roidt (2017).

Figure 2.1 A rough timeline of key events in the nexus concept evolution

In research the concept of virtual water influenced the emergence of the nexus in the 2000s (Allan, 2003). The concept tackles the interlinkages between water scarcity and food trade. It received support in the Third World Water Forum in Tokyo (2003), and Allan's advice to the Water Advisory Committee of the World Economic Forum influenced the theme and outcomes of its annual meeting in 2008 (Al-Saidi and Elagib, 2017; Allan, 2003; Muller, 2015).

In the years between 2008 and 2011, the development of the WEF Nexus culminated in different important milestones (see also table 2 in Leck et al., 2015 and timeline in UNECE, 2018). The annual meeting of the World Economic Forum in 2008 called for an increased understanding of linkages between energy, water and food (Wichelns, 2017). In 2011 the World Economic Forum's Report *Water Security: The Water-Energy-Food-Climate Nexus* emphasized this point again and connected the nexus to the simultaneous achievement of water, energy and food security (see also Bazilian et al., 2011; Leck et al., 2015).

In the same year, Holger Hoff from the Stockholm Environment Institute published the article 'Understanding the nexus' (Hoff, 2011). He outlined the benefits of the WEF nexus approach and placed it within the green economy (Lawford et al., 2013; Leck et al., 2015; Schwärzel et al., 2014). This served as a background paper for the subsequent nexus conference in Bonn. The conference marked the emergence of the WEF nexus as part of the solution to a green economy (see different representations in Figure 2.1). The Bonn conference served as a contribution to the Rio+20 conferences. Rio+20 emphasized the importance of address energy, food and water security in a sustainable manner. The nexus discussions continued with a second large conference in Chapel Hill, United States in 2014. There, a nexus declaration was authored and handed to the United Nations Secretary General as input for formulating the Sustainable Development Goals (SDGs) (Leck et al., 2015).



Source: Author, with thanks to Serena Caucci, Sabrina Kirschke, Angela Hahn and Andrea Müller.

Figure 2.2 Elements to take into consideration when beginning nexus work, to be thought of in a circular manner

The nexus has thus come a long way. But what is the nexus actually? How has it been tackled in the past years? And what are some of the tools and methodologies that nexus research is using?

Figure 2.2 provides an overview of the three core elements that we believe to be of essence when setting out to do nexus (research) work. As a first step, the scope of the issue needs to be delineated by (a) determining entry points for key constraint(s), (b) defining the boundaries of analysis (including that of social space) and (c) defining the end goal (most often to achieve a sustainable state of affairs). This should naturally lead to define which kind of nexus will be applied (resource versus sector nexus, WEF or other, etc.). The choice of the methodology for the assessment should follow a mixed-method approach that allows for knowledge generation in a transdisciplinary setting. Last but not least, the impact of the applied approach needs to be evaluated.

In this chapter, for each of these elements, we intend to (a) show the current diversity and to some degree lack of clarity and (b) offer some subjective suggestions towards a common set of working modalities.

2.2 OVERVIEW OF NEXUS CONCEPTS AND THEIR DEFINITIONS

Nexus concepts abound. This section intends to give a brief overview of the WEF nexus as the centrepiece of nexus work, different variations of it, definitions and descriptions of nexus in nexus projects, and challenges with diversity. For a good visual overview of how nexus frameworks and their representations evolved please refer to chapter 2 of Simpson et al. (2020).

2.2.1 Water-Energy-Food Nexus

The WEF nexus establishes that the water, food and energy sectors are interrelated and interdependent (Hoff, 2011). Hoff's definition states:

> The nexus approach highlights the interdependence of water, energy and food security and the natural resources that underpin that security – water, soil and land. Based on a better understanding of the interdependence of water, energy and climate policy, this new approach identifies mutually beneficial responses and provides an informed and transparent framework for determining trade-offs and synergies that meet demand without compromising sustainability.

Most articles and research projects base their work on the above definition to some degree. For the WEF nexus, the transition to a green economy is key and intended to be reached through greater policy coherence and increased resource efficiency (Hoff, 2011). By reducing trade-offs and enhancing synergies, the WEF nexus aims to augment simultaneously water, energy and food securities (Hoff, 2011). Three aspects are of relevance here: (1) 'investing to sustain ecosystem services' as they form the basis of our natural capital; (2) 'creating more with less', as increased resource efficiency alleviates resource scarcity; and (3) 'accelerating access, integrating the poorest', accelerating development and sustainability while reducing poverty (Hoff, 2011: 14f.).

2.2.2 Learning from Integrated Management

The rationale for the WEF nexus results in large part from the concept of integrated water resource management (IWRM). While some authors argue that the nexus has been established on the track records of previous integrated management approaches (Al-Saidi and Elagib, 2017; Kurian, 2017), others see the nexus as a response to the perceived failure of IWRM (de Loe and Patterson, 2017; Muller, 2015). IWRM was born out of the idea that water cannot be managed in a siloed approach. It was understood that water users as diverse as domestic water suppliers, energy producers, agriculture or the ecosystem need to be considered when managing water resources. Hydrologists and water engineers familiar with systems analysis put forward the IWRM approach (Allouche, 2016) as a systems approach to the study of water resources (Wichelns, 2017) and an interdisciplinary and *holistic* way of managing them. The definition of IWRM that is most widely accepted and of relevance today was given by the Technical Committee (former Technical Advisory Committee) of the Global Water Partnership. It states that IWRM is ‘a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems’ (GWP, 2000: 22).Today, IWRM is the leading and most widely accepted paradigm of water management (Jeffrey and Gearey, 2006). Even though controversially discussed and criticized, the aim to implement IWRM around the globe is ongoing. The dedication of SDG 6.5 to IWRM shows that it is high on the agenda in today’s approaches to managing water resources (United Nations, 2015).

To better assess the arguments for the perceived failures of IWRM and mistakes that should not be repeated in nexus thinking, Roidt (2017) conducted a literature analysis on the elements of criticism towards IWRM (and two further integrated management approaches).

From the analysis the following aspects emerged as key:

- The approach is ambiguously defined – IWRM seems to be a mindset rather than a policy.
- Operationalization is difficult or even impossible – there are perceived problems in the translation from research into practice.
- Implementation is difficult or even impossible – case evidence shows no clear achievement of the outcomes aimed for.
- IWRM is in the dichotomy between holism and reductionism – there is the a priori assumption that holistic approaches will achieve better results.
- Some assessment and scrutiny on the IWRM has yet to be conducted – effects of IWRM versus non-IWRM have not been thoroughly assessed.

These issues clearly need to be taken into account when establishing a new holistic concept such as the nexus, where the ambition of integration extends far beyond the water sector. The question then becomes how to overcome the vagueness of the nexus to deliver tangible results without losing the complexity which the concept inherently has.

In addition to the general challenges listed above, a key element for implementation refers to the setting of boundaries. IWRM is bound to the watershed and critics suggest that it overlooks the importance of administrative boundaries as relevant for implementation (de Loe and Patterson, 2017; Graefe, 2011; Kurian, 2017). Defining relevant scales of analysis determines the accuracy of diagnosis and the effectiveness of the implementation (Alcamo et al., 2003; Kissinger and Rees, 2010). Spatial resolution determines the visibility of objects and relations. If systems boundaries are too small, important factors influencing the system may be missed, whereas if they are too large, detail on the specific process may be lost. By mixing in and contrasting different spatial perspectives, a multi-scalar approach could provide for more comprehensive analyses.

At the same time, care must be taken to not be generic, unspecific, or overly ambitious in tackling scales of analysis. Nexus literature call for tackling multiple scales, including those of resources, sectors, governance, etc., but remain vague about how to reconcile those. Avellán et al. (2017) argue that system boundaries for nexus implementations should be 'clear, wide and flexible'. Here, the system boundary is defined as the geographic overlap of at least two resource system boundaries. Thus, when considering for instance water and soil resource systems (soil as one of the biophysical resources needed for food production), the geographic boundary would be drawn at the overlap of the (farm) land in question and the respective (sub-)surface watersheds. The idea is to assess the nexus resource flows across those sub-systems only in the area where they overlap, treating assessments of resource flows and balances within each sub-system as external input values to the nexus system. This system is therefore adaptable to the circumstance in question but is limited to the geographic system perspective. The respective social, legal, economic, or governance system(s) can be linked to this in a multi-scale manner as was for instance done in a nexus project that determined the sustainability of wastewater treatment systems (Avellán et al., 2019).

2.2.3 Aims of the 'Nexus' in the Scientific Literature

Since the publication of Hoff's seminal paper nexus literature have taken off. In the past 10 years several thousands of publications have been published in peer-reviewed journal articles, quadrupling the yearly production since 2010 to roughly 2000 publications in 2019 (Figure 2.3). Aspects of energy, water and food can predominantly be found, but also climate, land and waste are considered in these publications, without being specific enough about the particular interlinkages that were assessed. Curiously, the food-energy-water nexus is more commonly found in searches than the WEF nexus (water-energy-food). However, this is only the view through the perspective of ScienceDirect and could be different when considering other search engines.

Roidt and Avellán (2019) in their analysis of the goals and features of integrated resource management approaches as well as nexus approaches showed that all concepts strive towards sustainability and that the literature defined the goals of the WEF nexus with the following elements (see Roidt and Avellán, 2019, table 2):

- achieve water, energy and food security;
- support sustainable development and the SDGs;
- increase resource efficiency and optimization;
- inform resource governance and promote rational decision making;
- enhance policy coherence and cooperation within and between sectors; and
- shift from integration within the sector to cross-sectoral integration.

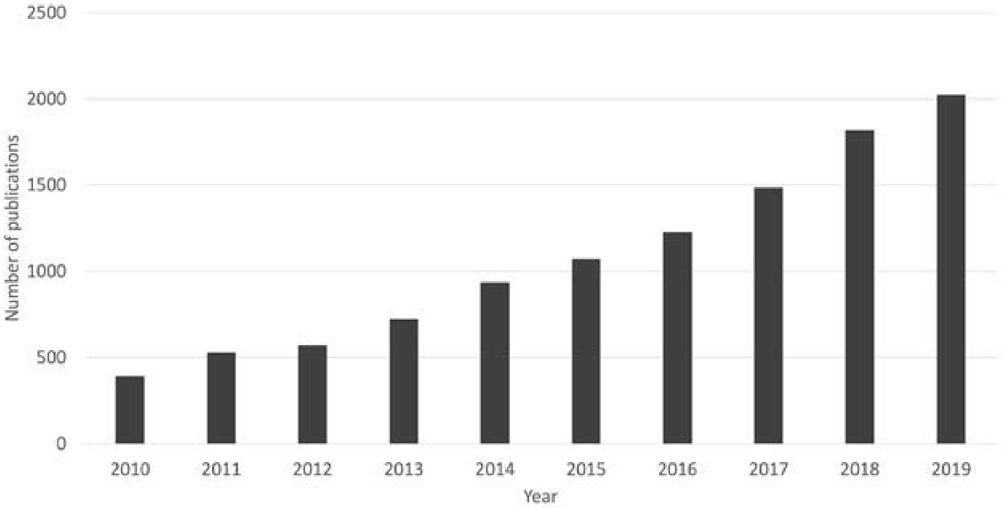
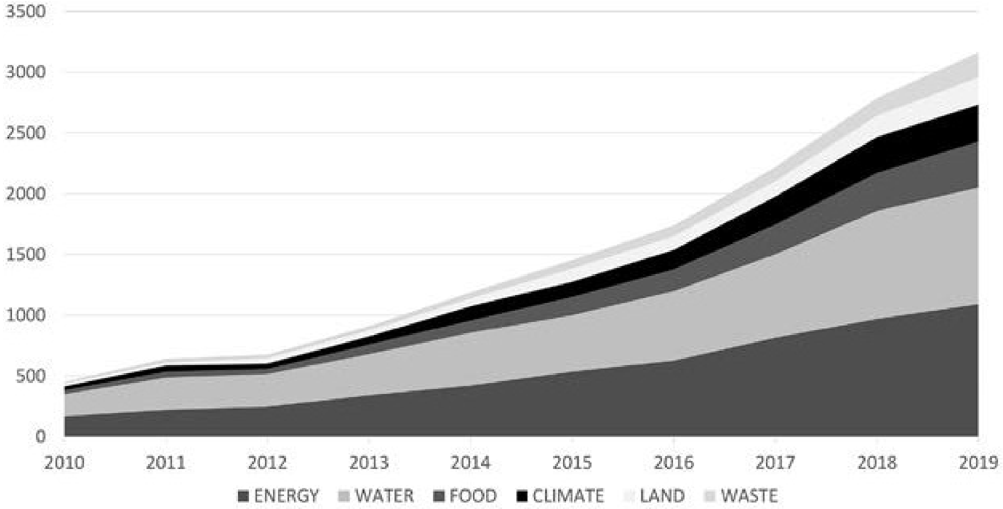


Figure 2.3a *Number of nexus publications per year (not cumulative)*



Note: The search was performed in September 2019 in ScienceDirect for articles published between 2010 and 2019 containing the terms ‘nexus’ and ‘energy’, ‘water’, ‘food’, ‘climate’, ‘land’, or ‘waste’ in the title.

Figure 2.3b *Related to each of the aspects*

2.2.4 Evolution Since? Nexus Definition in Projects

Not only have publications expanded, but also a number of (research) projects have also seen the light of day. Many nexus projects in Europe and across the globe have since been financed and implemented. Several authors have underscored the need for a (more) coherent conceptual framework for nexus projects and assessments (Endo et al., 2017) without it ‘become[ing] a rigid concept' (Al-Saidi and Elagib, 2017). Table 2.1 summarizes 22 projects and their definitions that were easily accessible online in an attempt to roughly characterize the definitions proposed there.

Similar to the distribution of keywords in academic publications, water (36 mentions), energy (32) and food (24) are, in those projects, the most prominent words used in the definitions of their nexus, but also climate, ecosystem, land and waste are sectors or resources that can be found. 'Water energy food' is used 17 times throughout the project definitions. 'Security' is mentioned six times and four times in conjunction with 'food', which is in contrast to Galaitsi et al. (2018) who demonstrated that water security is the main motivator for WEF nexus studies, rather than food or energy security. 'Resources' (12) is used more frequently than 'sectors' (8), and 'between' (11) is employed more frequently than 'across' (7). Concepts like 'trade-off(s)', 'synergy(ies)', 'interconnection(s)/interconnected', 'interlinkage(s)/interlinked', or 'interdependence(ies)' can each be found less than three times throughout the definitions, however, most definitions make use of those concepts in one way or another. This analysis simply shows (1) the predominance of the WEF nexus, (2) the importance of security for food and others, (3) the relevance of resources over sectors, and most critically (4) how dispersed the terminology is when defining the connections/interlinkages/interrelations of the nexus.

While in principle attempts for narrowing the framework could be misleading and actually counterproductive (Hoff, 2018) and the lack of consistent definitions across projects and initiatives may not be a problem, it could lead to the erosion of confidence in the approach as well as an overall lack of understanding across projects. Building an ontology of nexus concepts could be useful to improve clarity and create a common understanding (Kumazawa et al., 2017).

Roidt and Avellán (2019) showed that the lack of definitions and thus understanding of the word 'integration' in different communities of integrated resources management pose a challenge to overcome disciplinary divides. To overcome this lack of definition for the nexus they suggest the following for the definition of 'integration':

> to describe integration with the concept of the category of integration and the term aspect which includes systems, subsystems and other aspects alike. Different aspects of an approach have to be integrated. An aspect is defined as '[a] particular part or feature of something' (Oxford Dictionary, 2017, paragraph 1). In this case, something would refer to the approach. Examples are the integration of different systems (e.g. water-land), subsystems (e.g. surface water-groundwater) or even other aspects such as waste types-treatment or upstream-downstream. To grasp this issue, the concept of the category of integration is suggested here. Such a category of integration describes the connection between two aspects of the integrated approach. A category may consist of many interlinkages which connect the two aspects. (Roidt and Avellán, 2019)

2.3 NEXUS METHODOLOGIES AND TOOLS: EFFECTIVE DECISION MAKING FOR THE NEXUS

The sections above show the diversity in which the nexus (research) landscape is operating. The flexibility of the nexus approach that allows for assessing the biophysical interlinkages at the same time as economic, social, governance and policy interventions is also its curse. Galaitsi et al. (2018) identified that empirical nexus research has used different rationales to address nexus questions (key constraints), used multiple entry points to assess nexus problems (intervention points) and pursued different goals with their interventions (potential outcomes).

Table 2.1 *Overview of nexus definitions in nexus projects*

Project	Nexus definition
5TOI (Energy, Water and Agriculture in the South Mediterranean Neighbourhood), www.5toi.eu/	The nexus highlights the interdependencies between the water, energy and food sectors, and the need to pursue an integrated management framework across the three sectors. The water-energy-food security nexus framework is particularly suited to the Arab region given the stressors, constraints and strong interdependencies between sectors.
BRIDGE (Building Resilience in a Dynamic Global Economy – Complexity across Scales in Brazil), www.ceenrg.landecon.cam.ac.uk/research/the-bridge-project	A complex system involving many interactions between social and natural components, of which future behaviour is not well understood.
CECAN (Centre for the Evaluation of Complexity across the Nexus), www.cecan.ac.uk/	'What works in practice' can be very difficult to ascertain, especially with policies that cut across the energy, environment and food nexus domains, where urgent matters such as the 'energy trilemma', loss of biodiversity, climate change, poverty and challenges to health and well-being are entangled in complex ways.
CLEWs (Climate, Land, Energy and Water Strategies to Navigate the Nexus), www.kth.se/en/itm/inst/energiteknik/forskning/desa/researchareas/clews-climate-land-energy-and-water-strategies-to-navigate-the-nexus-1.432255	The research on climate, land use, energy and water strategies develops an integrated systems approach. It investigates interconnections between these different resource sectors, to determine the effects changes in one sector might have on the others, and identify counterintuitive feedbacks in these integrated systems.
CLISWELN (Climate Services for the Water-Energy-Land Nexus), www.jpi-climate.eu/nl/25223443-CLISWELN.html	The water-energy-food nexus is a conceptual framework that presents opportunities for greater resource coordination, management and policy convergence across sectors.
DAFNE (Decision Analytic Framework to Explore the Water-Energy-Food Nexus in Complex Trans-Boundary Water Resource Systems of Fast-Developing Countries), http://dafne-project.eu/	The nexus approach highlights the interdependence of water, energy and food security and the natural resources that underpin that security – water, soil and land. Based on a better understanding of the interdependence of water, energy and climate policy, this new approach identifies mutually beneficial responses and provides an informed and transparent framework for determining trade-offs and synergies that meet demand without compromising sustainability.
Food and the Circular Economy, www.circularfood.net/	The circular economy is defined as one in which maximum value is extracted from resources during use, avoidable waste is eliminated and unavoidable waste reused or recycled. Given the planet's finite capacity to provide resources and absorb waste, the circular economy is thought preferable to the traditional linear business model of resource exploitation, manufacture, consumption and disposal. A continuous improvement process, driving innovation and competitiveness, the circular economy concept is gaining traction in many countries and industries.
IS-WEL (Integrated Solutions for Water, Energy and Land Project), www.iiasa.ac.at/web/home/research/researchProjects/Nexus_Solutions.html	The water-energy-land nexus is characterized both through trade-offs as well as multiple co-benefits across distinct policy objectives.

Project	Nexus definition
MAGIC (Moving towards Adaptive Governance in Complexity: Informing Nexus Security), http://magic-nexus.eu/	Nexus a: When the term nexus is used in relation to biophysical events taking place in the external world, the nexus refers to the entanglement over biophysical flows (water, energy and food) determined by the expected characteristics of the metabolic pattern of sociological systems. Nexus b: When the term nexus is used in relation to the process of governance and policy making, the nexus refers to the acknowledgement that existing institutions should be capable of expressing an effective system of governance (policy coherence and integrations) in relation to the three securities (water, energy and food). At the moment this is not achieved and this is a reason of concern when considering existing trends of population growth, consumption per capita and the aggregate requirement of water, energy and food inputs against the deterioration of ecosystems' health all over the planet. Nexus c: When the term nexus is used in relation to the problem of scientific inquiry, the nexus refers to the acknowledgement of the existence of an elephant in the room – i.e. the Cartesian dream of prediction and control is smashing against the complexity of the nexus. At the moment, we do not have effective analytical tools capable of generating useful scientific information for dealing with it.
Nexus in Deltares, www.deltares.nl/en/issues/nexus-water-energy-food-2/	The water-energy-food nexus centres on the interaction between the two factors that have the most impact on the availability of fresh water: energy and food production.
Preparation of the Nexus Assessment in South East Europe, www.gwp.org/en/GWP-Mediterranean/	The water-energy-food nexus approach was introduced in the global natural resources management agenda to facilitate the enhancement of water, energy and food security while preserving ecosystems and their functions, including under conditions of climate variability and change, by increasing efficiency and productivity of resources, reducing trade-offs, shifting towards more sustainable consumption patterns and improving demand management, building synergies and improving governance across sectors.
Scaling and Governance in the Water-Food-Energy Nexus	Aspects of global change that we highlighted are changes in water demand, land use and climate. Currently we are working on how future changes in water systems affect the competition for water between the energy, agricultural and environmental sectors. In the agricultural sector, we focus mostly on irrigated water demands and within the energy sector we focus on water for hydropower, biofuels and the cooling water needs of thermoelectric power plants.
SIM4NEXUS (Sustainable Integrated Management of Water-Land-Food-Energy-Climate for a Resource-Efficient Europe), www.sim4nexus.eu	Water, land, food, energy and climate are interconnected, comprising a coherent system (the 'nexus'), dominated by complexity and feedback. Putting pressure on one part of the nexus can create pressure on the others. Management of the nexus is critical to securing the efficient use of our scarce resources.
STEPPING UP (Sustainability for Water, Energy and Food)	The 'water-energy-food nexus' describes the interactions between the water, energy and food systems. Although regulated in silos, none are truly independent.
United Nations University: Nexus Approach to the Sustainable Management of Environmental Resources, www.flores.unu.edu	The nexus approach to environmental resources management examines the inter-relatedness and interdependencies of environmental resources and their transitions and fluxes across spatial scales and between compartments. Instead of just looking at individual components, the functioning, productivity and management of a complex system is taken into consideration.

Project	**Nexus definition**
Vaccinating the Nexus: Learning from Crisis in Cities, www.cityleadership.net/vaccinating-the-nexus	Interdependencies between water, energy and food systems, which is known as the water-energy-food nexus.
Water, Energy and Food Security Resource Platform, www.water-energy-food.org/start/	The nexus approach highlights the interdependence of water, energy and food security and the natural resources – water, soil and land – that underpin that security. The nexus approach identifies mutually beneficial responses that are based on understanding the synergies of water, energy and agricultural policies.
Water-Food-Energy-Ecosystem Nexus, www.unece.org/env/water/nexus	The nexus term in the context of water, food (agriculture) and energy refers to these sectors being inextricably linked so that actions in one area commonly have impacts on the others, as well as on ecosystems.
WEF Nexus Research Group, https://wefnexus.tamu.edu/	The interconnection of water, energy and food resources is highly complex and the availability of these resources is increasingly stressed by climatic, social, political, economic, demographic, technologic and other pressures. Sustainably addressing these challenges requires a better understanding of the nexus formed by the interconnections between the resources and will lead to a more equitable allocation and improved management of them.
WEFE Nexus Flagship Project, https://ec.europa.eu/jrc/en/event/workshop/workshop-water-nexus-mediterranean	Water use is indispensably related to food production, energy generation and the functioning of ecosystems. Such complex interactions define the water-food-energy-ecosystem nexus.
WEFWEBs, www.gla.ac.uk/research/az/wefwebs/	Our water, energy, food and waste systems are interconnected, and impacted by climate and demographic change. The nexus seeks to define the interdependencies between the different systems and improve our understanding. There are dynamic and interlinked interdependencies across the nexus networks which are physical (water, waste, energy and food), social and political (individual, regulatory and policy), ecological and digital at multiple, nested scales (local, regional and national) and temporally.
WIRE (Water and Irrigated Agriculture Resilient Europe), www.eip-water.eu/WIRE	WIRE will facilitate innovation uptake in the complex, multi-faceted irrigated agriculture reality and market. Accordingly, water reuse should be efficient in irrigation, energy should be saved in irrigation, and integrated agricultural water should be managed under drought.

Despite this seeming chaos, we postulate that all nexus efforts strive towards better decision making. Decision making aims at maximizing the gains, benefits, or achievement of defined interests (Edwards, 1954; Tversky and Kahneman, 1986), thus minimizing the maximum losses or maximizing the minimal gain. In general, there are common aspects that result in a final decision or choice: (1) identification of the interest, goal, or aim; (2) framing and decomposing; and (3) an evaluation (Müller et al., 2020). Transdisciplinary research principles have been argued to be of use to work on sustainability problems (Brandt et al., 2013) and could therefore be of use also for addressing nexus issues. Adopting transdisciplinary research principles in nexus (research) could thus follow these three broad levels: (1) gaining a better understanding of the current system (system knowledge); (2) shaping an understanding of the desired aim (target knowledge); and (3) discovering pathways of how to get from the current system to the future target state (transformation knowledge). We argue that these two thought systems of decision making and transdisciplinary levels can very much work together, since obtaining system knowledge is required to identify interests, goals and aims as well as to frame and decompose the issues; obtaining target knowledge is mandatory to understand the standard against which one is evaluating the current system; and transformation knowledge is helpful towards the implementation of the decisions.

The sub-sections below give a subjective perspective on the current state of affairs in nexus research with respect to knowledge generation for decision making.

2.3.1 Framing and Decomposing Information

A variety of authors argue that, in nexus literature, a strong focus is laid on gaining system knowledge through the understanding of sector or resource interlinkages and determining ‘critical’ interlinkages (e.g. Dai et al., 2018) ‘understanding the nexus’ (Dargin et al., 2019; Zhang et al., 2018). Models often borrowed from disciplinary approaches to support nexus research are used (see Table 2.2 and Roidt, 2017). Some studies ask for new tools and methods to better describe and understand nexus issues (Al-Saidi and Elagib, 2017; Kurian, 2017). To avoid ‘paralysis by analysis’, it seems useful to identify those interactions that are key in specific situations (de Loe and Patterson, 2017). This may reduce the overwhelming complexity that the nexus implies. Nevertheless, innovative analysis tools need to be developed to understand the nexus system and inform about trade-offs and synergies of current but also potential future states. Several studies point to the need for appropriate nexus tools which would enable an integrative assessment of the considered nexus components under study (Al-Saidi and Elagib, 2017; Albrecht et al., 2018; Daher et al. 2017). However, care must be taken in providing clarity as to what ‘integration’ entails, as the term is, in fact, poorly defined in the literature on integrated resource management approaches (Roidt and Avellán, 2019).

The following studies highlight the lack of integration that most nexus methods exhibit. Zhang et al. (2018) conducted a comprehensive analysis of methods used in nexus research. This led to three categories of increasing complexity: (1) internal relationship analysis, which assesses the unilateral or bilateral interlinkage between two or more aspects; (2) external impact analysis, which further includes external factors that influence nexus relationships such as population growth or climate change; and (3) the evaluation of the coupled system with a focus on overall system resilience or sustainability. Most methods used relate to analyses that assess the current state of resource use concerning one or more nexus aspects (e.g. litres

Table 2.2 *Top five models used in integrated water resource management*

Rank	Name	NoP	Description
1	SWAT	54	'predict the impact of management on water, sediment, and agricultural chemical yields in ungauged watersheds' (Gassman et al., 2007: 1212)
2	WEAP	30	'place … water supply projects in the context of demand-side issues, as well as issues of water quality and ecosystem preservation' (Sieber and Purkey, 2015: 1)
3	Modflow	26	simulate groundwater flow 'associated with external stresses, such as wells, areal recharge, evapotranspiration, drains, and rivers' (Harbaugh, 2005: 1)
4	ACRU	14	'integrate … the various water budgeting and runoff producing components of the terrestrial hydrological system' (Smithers and Schulze, 1995: 1–2)
5	CROPWAT	13	Calculate reference evapotranspiration, crop water and irrigation requirements, water supply and irrigation schedules under different management conditions (FAO, 1992)

Note: NoP = number of nexus publications in which the model was mentioned.
Source: Roidt (2017).

of water used for irrigation of a particular crop in a particular place and/or of energy needed to abstract this water).

Dai et al. (2018) identified a number of used nexus tools. All of them, however, had serious limitations in terms of applicability, ease of use and feasibility due to data limitations. Dai et al. (2018) showed that for the water-energy nexus, most tools focus on the first level of nexus research (i.e. understanding the nexus) but less so in implementing the nexus. Moreover, virtually all of them were targeting mainly the scientific community, aiming at increasing systems understanding, while tools applicable for governance and implementation were hardly available. Similarly, Albrecht et al. (2018) found that modelling tools applied in nexus studies performed poorly with regard to the representation of interlinkages of resources sectors.

Dargin et al. (2019) identified the need for determining the complexity of a model to be able to choose the one that best fits the local context and needs. Here, the tools can be used for three levels of interventions: (1) integration (similar to Zhang et al., 2018); (2) last mile (centred on supporting stakeholder needs); and (3) risk-informed planning (to reduce risks and enhance prevention). As with the findings above, the authors found that most models deal with integration, and the least with last-mile issues to support stakeholder needs on the ground.

Making use of readily available tools does imply in most cases that those tools have not been developed to represent a nexus mindset. Instead, their model structure typically reflects a more sectoral view on the respective resource. Integrated management approaches such as IWRM, integrated solid waste management and integrated natural resource management have developed their own models over time. The Nexus Tools Platform describes and can help select from over 300 models with a focus on water, soil and waste resources (Mannschatz et al., 2016). An analysis by Roidt (2017) showed that far more of these models have been developed for the purpose of IWRM (86), integrated solid waste management (22), or integrated natural resource management (5), and with the majority (228) not being linked to any of these approaches. The top five most cited models under IWRM also mostly focus on describing and quantifying interlinkages and resource flows (Table 2.2). Hence, the use of models from an integrated management approach may help in describing resource flows within their sectoral aspects but may not be placed so well to describe interlinkages with other aspects, e.g. food, land, or energy.

In general, it does not seem feasible to develop a comprehensive nexus tool which considers all processes related to resources including the required (case-specific) level of detail and spatial and temporal resolution. Instead, each single nexus study develops or applies the most appropriate (suite of) modelling tool(s) from available tools in a context-specific manner. The selection criteria need to be defined in a systematic manner, starting with defining the specific research question (Daher et al. 2017), paying particular attention to the respective system boundary (Avellán et al. 2017), and considering also tool complexity (Dargin et al., 2019).

2.3.2 Evaluating the Aspects of Interest

As highlighted by Dai et al. (2018) and Dargin et al. (2019), few models exist that help move beyond the 'understanding the nexus' phase, i.e. systems knowledge. To be able to provide those pathways an evaluation of the status quo with respect to the desired target state needs to be undertaken, e.g. through sustainability assessments or other similar tools.

To overcome these challenges, nexus work therefore does not exclusively rely on quantitative methods to assess interlinkages but to a certain degree also on qualitative methods in particular for describing and understanding the context. They also consider the intervention of stakeholders in selecting the most appropriate indicators and interlinkages as crucial.

A main challenge in nexus assessments resides in the multiple entry points under which a situation can be analysed and evaluated. Depending on the stakeholder mix the type and quality of information available can vary drastically; and so can the goal. Avellán et al. (2019) highlight the importance of consciously choosing and actively encouraging the participation of stakeholders; especially those that hold information, can contribute to the solution and are involved in decision making on the particular (research) question. They further show that by conducting a thorough stakeholder analysis new critical stakeholders can be unearthed that would otherwise not be considered, such as local community leaders in decision-making processes. A recommended methodology to undertake stakeholder identification can be found in Reed et al. (2009), where the main aim is to describe 'Who is related to the problem and how'. Stakeholders here are defined as: 'Social actors, organization, institutions, community, individuals, groups, who can be affected by or can affect a phenomenon'. This selection is based on the assumption that 'Only by understanding who has a stake in an initiative, and through understanding the nature of their claims and inter-relationships with each other, can the appropriate stakeholders be effectively involved in environmental decision-making' (Reed et al., 2009).

Indicator selection is also done through a variety of processes and is often comprised of context indicators (often qualitative) and specific indicators (often quantitative). As such, the United Nations Economic Commission for Europe uses both national indicators and basin indicators as screening, perspectives and assessment-specific indicators. The term indicator is often used interchangeably with parameter or variable, where the term parameter or variable describes the actual value of something (e.g. the pH value of water), and the term indicator is often used when that value can be set into context with a certain threshold value (e.g. pH7 is good for aquatic life). Flammini et al. (2014) developed an extensive catalogue of potential nexus parameters and indicators that relate to nexus interlinkages (e.g. energy consumed versus amount of desalinated water). In other cases, the dimensions of sustainability – environmental, economic, social – were used to determine critical indicators (Benavides et al., 2019).

While indicator selection may not be deemed too challenging, the identification of critical interlinkages may be more difficult. In the Transboundary Basin Nexus Assessment, this is done in interactive sessions with the stakeholders using printed nexus diagrams. Flammini et al. (2014) provide a set of predetermined generic nexus interlinkages (both synergistic and antagonistic) which are for instance derived from biophysical realities. Through a two-pronged approach of stakeholder/expert input and a set of ex ante assumptions of what may be important interlinkages based on the development status of the country, site-specific interlinkages can be contrasted with national priorities.

2.3.3 Choosing a Way Forward

While indicator selection and identification of interlinkages is important, few approaches consider methodologies to foster transformation knowledge and to thus determine pathways to achieve the desired solution. As such Avellán et al. (2019) suggest a multi-method, interdisciplinary approach that considers a sustainability assessment, a wickedness analysis and a stakeholder network analysis to find pathways towards sustainable wastewater management systems (Figure 2.4). While all three methods describe the status quo of the situation (sustainable or not, degree of wickedness of the problem, strong versus weak tie stakeholder network) they also show entry points and pathways towards a more sustainable situation (investing in human resources to gather, share and communicate information, in particular that of a social and economic nature).

Serious gaming can also be an option to explore pathways towards more sustainable solutions. Games can help show visually the impacts that certain policy measures in one sector/resource use can have on another sector/available resource. The Nexus Game (https://nexus.socialsimulations.org/) gives players the chance to develop their countries as ministers of water, energy, agriculture, etc. During the game players intuitively understand the trade-offs and synergies between the WEF nexus sectors (Roidt, 2019).

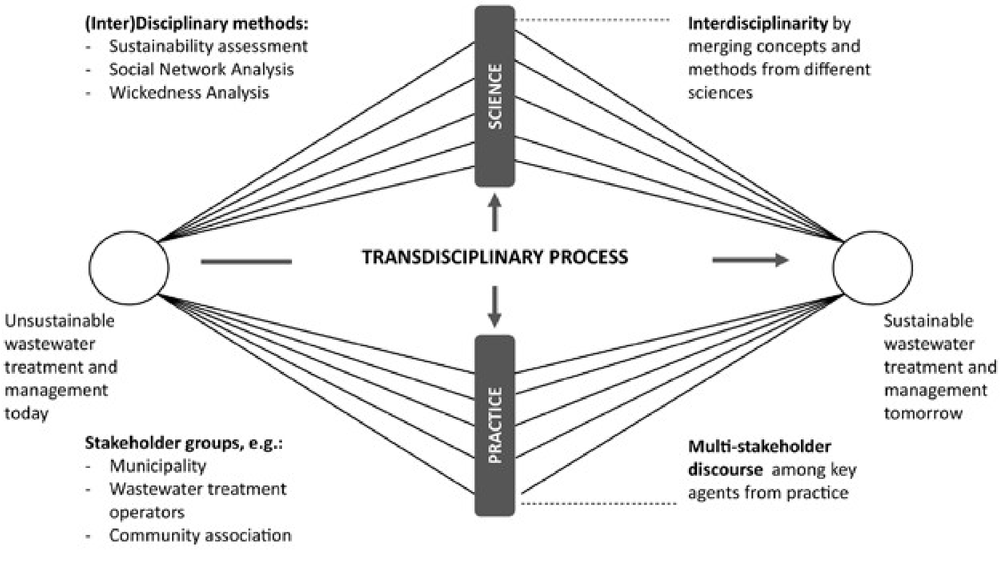


Figure 2.4 Multi-method interdisciplinary research approach towards sustainable wastewater management

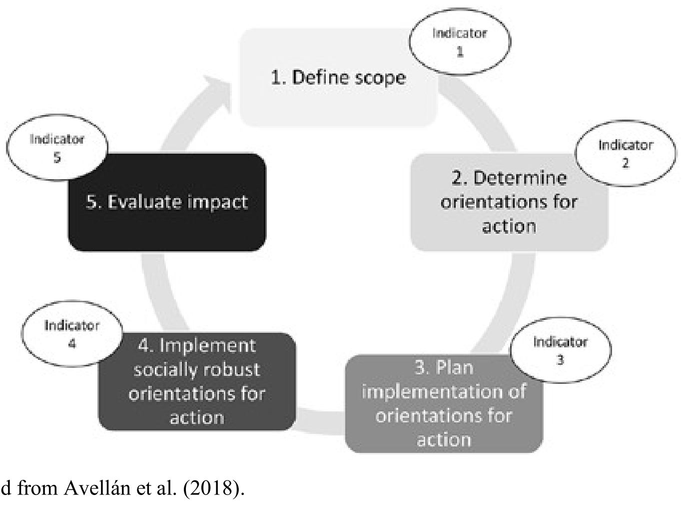
SIM4NEXUS has developed such a game (http://seriousgame.sim4nexus.eu/), where policy cards such as changes in carbon sequestration measures can be used. These policies have a direct impact on the model information running in the background of the game. After a five-year cycle the effect of the policies can be seen in the level of 'Nexus Health' indicators such as the share of renewable energy being used. The aim of the game is to 'explore how policies impact on different Nexus components' (www.sim4nexus.eu/page.php?wert=SeriousGame).

Similar to the concept of 'Nexus Health', a few researchers have proposed an all-encompassing nexus index. The idea here is to obtain a metric with which to assess the state of 'nexusness' of one case, to compare different cases, or to assess the evolution of the same case over time. Simpson et al. (2020) provided a global WEF nexus ranking based on a set of 21 indicators that are available in virtually all countries. They showed that developed countries generally score higher in the WEF nexus ranking than economies of transition or developing countries.

2.4 EVALUATING THE NEXUS

Some of the criticism of the nexus as well as that towards integrated management approaches was towards the lack of evidence-based improvement or success. Was it really worth the effort of conducting these complicated activities? Was impact being achieved? What has changed? And how is success defined and eventually measured?

An 'easy' answer could be that the level of 'nexusness' has increased, i.e. the Nexus Index as mentioned above is higher. Other authors have developed 'full-scale nexus assessment methodologies'. Their primary intention is to support implementation at specific levels or scales but to a certain degree they can also help set criteria for the evaluation of success. In Avellán et al. (2018), a five-step nexus approach is presented that is based on a project management cycle. For national-level assessments, the methodology developed by Flammini et al. (2014) seems useful. It describes a three-phase approach embedded in a stakeholder dialogue



Source: Adapted from Avellán et al. (2018).

Figure 2.5 *Revised nexus process description*

Table 2.3 Details of indicators for each new step

Step	Indicator
1. Define scope	● Number and type of stakeholders impacted by the sustainable development issue ● Category and number of integration(s) across aspects[a] and type of interlinkage between resources, between resources and services and across sectors ● Level of transdisciplinarity in project design (number of partners and level of involvement)
2. Define research approach	● Type of boundary definition (multi-scalar, depending on disciplinary methods applied) ● Degree and type of interdisciplinary research methods applied (number of disciplinary methods and degree of interdisciplinarity achieved)
3. Identify nexus orientations for action	● Level of transdisciplinarity in project implementation (number of partners and level of involvement) ● Degree of reduced trade-offs and increased synergies
4. Introduce 'socially accepted' nexus orientations	● Degree of enhanced capacity in decision making ● Level of potential for out and upscaling
5. Evaluate the impact	● Degree of social acceptance ● Degree of enhanced sustainability

Note: [a] See Roidt and Avellán (2019) for the definition of categories of integration.

with an extensive indicator list. For transboundary assessments, UNECE (2015) developed an approach which focuses on determining the increased sharing of benefits when applying a nexus approach. For local studies, Terrapon-Pfaff et al. (2018) developed a four-step system for small-scale interactions. The steps are: (1) qualitative mapping of the links between the water, food and energy sub-systems; (2) quantification of WEF nexus links; (3) identification of critical links; and (4) leverage of results.

Albeit not perfect, the nexus process in Figure 2.5 and Table 2.3 could be used to guide the nexus work and its criteria could be used to evaluate nexus (research) projects on a step-by-step basis. As such it serves not only as a framework to measure ultimate success but to a certain degree also as a quality control mechanism to check if the project is adhering to 'nexus principles'.

2.5 CONCLUSION

The nexus concept to achieve simultaneous water, energy and food security and thus move towards sustainability has received significant attention by researchers in the past 10 years. Noteworthy progress has been made in defining nexus concepts, applying tools and methods to assess the interlinkages and material flows between nexus aspects, and on selecting key interlinkages. However, less attention has been paid so far on determining the methods and tools to characterize pathways to achieve a sustainable or more efficient resource use to achieve that triple security. While scenario assessments can help to do so in part the complexity of the nexus requires the integration of new information such as policy impacts or stakeholder network relations that are so far absent from integrated resource management models and tools. Particularly striking is the lack of methods and strategies to evaluate the nexus.

Disciplinary approaches, e.g. from an engineering perspective, are not enough to grasp the difficult challenges of social and political realities that often hamper a sustainable and sustained solution. Scholz and Steiner (2015) propose to use transdisciplinary approaches to address real-world problems and their respective sustainable solutions. Overcoming the predominant fragmented disciplinary approaches by moving through interdisciplinary methods to transdisciplinary modalities may lead to more robust results. As such Scholz and Steiner argue that 'In a world of globalized challenges such as pollution, social injustice, migration and resource use, sustainable transitioning is a multidimensional and multiscale issue. Mastering these challenges calls for including experiential knowledge from multiple scales such as disciplinary knowledge related to a specific challenge' (Scholz and Steiner, 2015). Building on this definition, Brandt et al. (2013) propose three types of knowledge to be shared between all stakeholders: '(i) "system knowledge" the observation of the system, (ii) "target knowledge" the knowledge of the desired target state, and (iii) "transformation knowledge" the knowledge necessary for fostering transformation processes'.

Roidt (2017) provides the following set of recommendations to further develop nexus research:

- acknowledge the importance of synergistically increasing holistic and reductionistic knowledge;
- profit from specificity when operationalizing the approach;
- develop a specific language to facilitate interdisciplinary and transdisciplinary research in the nexus;
- be modest and focus on key interlinkages; and
- profit from clear indicators.

In conclusion, we argue that, for the nexus concept to be successful and useful for policy makers, all steps in the decision-making process need to receive equal attention and well-established transdisciplinary research principles should be taken into consideration. The whole approach should be deeply embedded in a thought-through stakeholder engagement plan in which these become active actors of change. Last but not least, the degree of change towards sustainability needs to be assessed to provide meaningful evidence that these complex undertakings are relevant.

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8.6 Publication 6

Unlocking the Impacts of COVID-19 Lockdowns: Changes in Thermal Electricity Generation Water Footprint and Virtual Water Trade in Europe

M. Roidt, C. M. Chini, A. S. Stillwell, A. Cominola

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Unlocking the Impacts of COVID-19 Lockdowns: Changes in Thermal Electricity Generation Water Footprint and Virtual Water Trade in Europe

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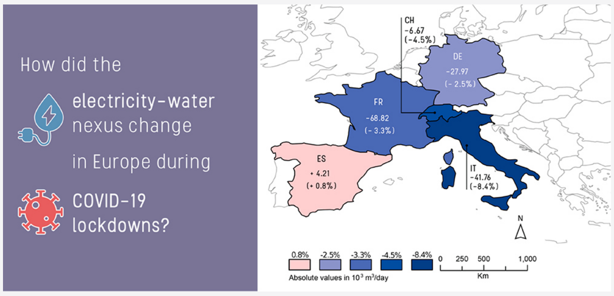

ABSTRACT: Drastic changes in electricity demand have been observed since March 2020 in Europe, after several countries implemented lockdown-like measures to contain the spread of COVID-19. We investigate the sensitivity of the electricity−water nexus in the European electric grid to large-scale behavior changes during the COVID-19 pandemic lockdown-like measures. We quantify changes in the blue virtual water trade between five European countries heavily affected by COVID-19 during the same period. As a result, the consumptive water footprint of thermal power plant operations in Europe decreased by 1.77×10^6 m^3/day during the COVID-19 lockdowns, compared to the average of the past four years. Reduced electricity demand accounts for 16% (0.29×10^6 m^3/day) of the decrease, while the remainder is attributable to changes in the electricity generation mix toward less water-intensive technologies before 2020 and during lockdowns. Virtual water transfers associated with electricity were also affected: Italy, a hotspot of COVID-19, reduced its water footprint by 8.4% and its virtual water imports by 70,700 m^3/day. Germany and France slightly reduced their domestic water footprint of electricity but increased their virtual water imports. These findings improve our understanding of the impacts of large-scale behavior and technological changes to the European electricity−water nexus.

INTRODUCTION

Since the appearance of a pneumonia of unknown cause in Wuhan, China, at the end of December 2019, the new coronavirus disease COVID-19 has spread worldwide with an outbreak that was declared a pandemic by the World Health Organization (WHO) on March 11, 2020.[1,2] As of April 19, 2020, the rapid spread of COVID-19 caused nearly 2.5 million confirmed cases in 185 countries worldwide, as reported by the Center for Systems Science and Engineering (CSSE) at Johns Hopkins University (JHU).[3] During March and April 2020, four of the five countries with the highest count of confirmed cases were located in Europe (Spain, Italy, France, and Germany).

As COVID-19 started its exponential spread in Europe in March 2020, nearly all European countries implemented quarantine and lockdown-like measures to contain the transmission. Recent studies analyzed the effectiveness of such measures on the spread dynamics of the COVID-19 pandemic,[4,5] as well as their consequences on several socioeconomic sectors, including lifestyles, telecommunications, and environment (e.g., 6−9 and references therein). Flights to and from Europe reduced.[10] European stock indices plummeted.[11] Schools closed in most of the regions,[12] and economic activities slowed down[13] as countries started implementing preventive quarantine and lockdown interventions. In Italy, one of the most severely affected European countries, electricity demand reduced by 18% in 1 week after the government instituted a national lockdown.[14]

During the same period, several newspaper articles around the globe reported on Europe's decreasing energy demand.[15−18] Involuntarily and rapidly, the European economy and its citizens had to embrace behavioral changes that led to lower electricity consumption compared to usage levels prior to the restrictions.

This letter builds on previous studies that adopted the concept of water footprint[19] to model the impacts of thermal electricity generation on water resources in Europe or other areas. Macknick et al.[20] contributed figures for water consumption of different thermal power plant technologies. These numbers have been revisited in multiple studies (e.g., ref 21). Other recent studies have then analyzed how thermal electricity generation is impacting water resources in Europe and worldwide (e.g., refs 22−26). Specifically, Larsen and

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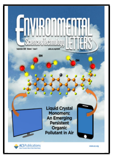

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Drews[27] studied the water use of electricity production in Europe and its changes over the long-term (1980−2015). Electricity trade in Europe was investigated by Abrell and Rausch.[28] The most recent and detailed study on the water footprint in the EU is provided by Vanham et al.[26] Chini and Stillwell[29] combined the topics of water footprint and electricity trade and calculated the virtual water embedded in electricity trade throughout Europe at a monthly scale (2010−2017). However, most of the above studies do not consider subannual dynamics of electricity demand and generation and model the system under normal operating conditions. An exception is a recent article in which seasonal water intensities of electricity generation were considered.[30] Here, we aim to contribute to the literature by evaluating the short-term changes of the European water footprint of thermal electricity and related impacts on virtual water trade during the COVID-19 pandemic.

We limit the scope of our analysis to the operational phase of thermal power plants, similar to previous research,[29] and query European electricity demand and generation data to address the following two research aims. We first investigate how changing electricity demand, and hence changing electricity generation, impacted the consumptive water footprint of thermal power plant operations in Europe during the COVID-19 pandemic quarantine and lockdown-like measures. Second, we quantify changes in the virtual water trade among five European countries strongly affected by COVID-19 during the same period.

Analyzing the impact on water resources of an exceptional, drastic, and rapid change in the electricity demand and generation in Europe represents a unique opportunity to improve our understanding of the sensitivity of the electricity−water nexus in the European electric grid to large-scale behavior changes, as compared, for instance, to technological improvements or adoption of different energy mixes. Understanding the subannual dynamics in the electricity−water nexus in the European electricity grid and rapid climate, technological, and collective behavior changes can ultimately facilitate the inclusion of nexus considerations in adaptive planning and management strategies. Adaptation strategies are key to ensure the resilience of critical systems and networks, especially in those parts of Europe, such as its Mediterranean basins, e.g., in Italy and Spain, already experiencing seasonal water scarcity, which will likely see increased pressure on water resources due to reduced precipitation and increased temperatures.[31,32]

■ MATERIALS AND METHODS

We first investigated whether Europe as a whole showed any change in its electricity generation after the implementation of quarantine and lockdown-like measures. We computed the time series of daily electricity load from January 1, 2020, to April 19, 2020, and then analyzed its deviation from the average values observed in the same period between 2016 and 2019.

Second, we calculated the consumptive water footprint of thermal power plant operations in Europe and its changes during the COVID-19 lockdown-like measures. The concept of water footprint is described in *The Water Footprint Assessment Manual*[19] and has been often applied to evaluate the embedded water resources of agricultural products (e.g., in refs 33 and 34). Water footprint refers to the amount of water consumed to create a product or process, including three categories: *green* water (i.e., rainwater stored in the soil and available to plants), *blue* water (i.e., consumed surface water or groundwater), and *gray* water (i.e., to dilute pollution). Here, we limit our analysis to the consumptive blue water footprint of electricity production in thermal power plant operations. The blue water footprint for hydropower is not included in our analysis, due to the lack of data availability at subannual temporal resolution. However, different studies reference the large contribution of hydropower to electricity water footprints; thus, future investigations to quantify the subannual water footprint of hydropower generation in Europe are needed to overcome the limitations of our results.[23,35] Green water is generally negligible in electricity production, when only power plant operations are considered.[23] Calculating the gray water footprint requires temperature data from rivers and cooling water that, to our knowledge, are not consistently available at the European scale. The water footprint of the energy fuels from a life cycle perspective is beyond the scope of this study.

Within this scope, the water footprint (WF) in m^3/MWh is calculated for each country (c) and day (d) as the product of daily electricity generation (e_f) from different fuel types (f) and the average water intensity per type (i_f)

$$\mathrm{WF}_{\mathrm{c,d}} = \sum_{\mathrm{c,d}}^{\mathrm{f}} i_{\mathrm{f}} \times e_{\mathrm{f}} \tag{1}$$

To compute WF (eq 1), we consider the same water intensity values (i_f) adopted by Macknick et al.,[20] averaged over different cooling technologies (further details are reported in Table S1).

Third, we analyze virtual water (VW) trade, which refers to the fraction of WF that is imported and exported by a country.[19] That fraction is calculated as the ratio between the exported electricity (x) and the generated electricity (g). We thus calculated VW as shown in eq 2

$$\mathrm{VW}_{\mathrm{c,d}} = \frac{x}{g} \times \mathrm{WF} \tag{2}$$

We completed the virtual water of electricity analysis using the electricity data published in the European Network of Transmission System Operators for Electricity (ENTSO-E) Transparency Platform. ENTSO-E publishes different electricity data sets with hourly or subhourly time resolutions for all European countries at the national scale.[19] The data sets from the past five years on load, generation aggregated by type, and physical flows over 25 European countries were used in this study. In particular, for the load analysis, we focused on the five countries with the highest absolute number of COVID-19 cases as of March 15, 2020, namely, Italy, Spain, France, Germany, and Switzerland. For the calculation of the WF and VW, some countries from the ENTSO-E data set were excluded from this study due to incomplete data sets in March 2020 (see Table S2 for a list of included/excluded countries). With regard to data processing, variables were summed to daily values and shifted in time to match the dates of the previous years with the same day of the week in 2020.

Given the time series of one of the analyzed variables of interest (e.g., the 2020 time series of water footprint of electricity generation in Europe), its mean values in 2020 before and after the lockdown-like measures were compared to their baseline values, i.e., the average values of the same variable computed over the past four years (2016−2019). The temporal change of a variable was then calculated as a

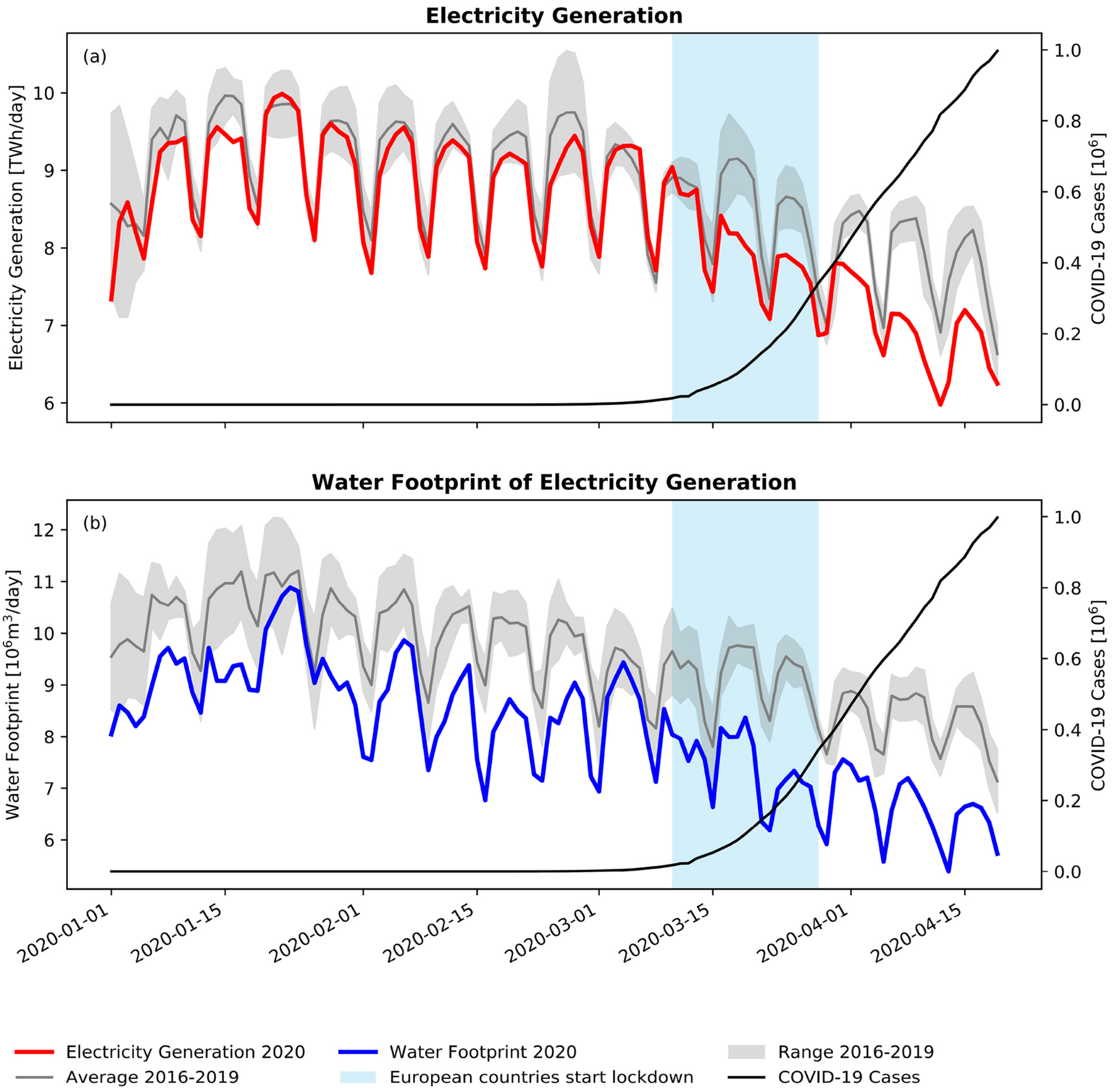

Figure 1. Electricity generation (red line in panel a) and related water footprint time series (blue line in panel b) in Europe from January 1, 2020, to April 19, 2020, compared to their average values and minimum−maximum range since 2016 (gray line and shaded gray area). The total number of confirmed COVID-19 cases in Europe (black line) and the time window when lockdown-like measures were implemented in different European countries (shaded blue area) are reported.

difference between the anomalies of its 2020 average values and the average 2016−2019 baseline values before and after the lockdown-like measure start date. This calculation is shown in the Supporting Information (eq S1). We disaggregated changes in the WF in Europe due to changes in the electricity mix during the lockdown-like measures as described further in the Supporting Information (eqs S2 − S6).

Finally, we included data on the number of COVID-19 cases published by John Hopkins University,[3] while we gathered details on preventive quarantine and lockdown-like measures and policies from different European newspapers or government announcements (Table S3). We investigated the five most affected countries as of March 15, 2020, namely, Italy (24,747 confirmed COVID-19 cases), Spain (7,798), Germany (5,795), France (4,499), and Switzerland (2,200) (Table S4).

■ RESULTS AND DISCUSSION

Changes in Electricity Generation in Europe. In the last 3 weeks of March 2020, most European countries implemented quarantine- and lockdown-like measures spearheaded by Italy on March 10, 2020. Later that week, the electricity generation in Europe started to decrease considerably, especially in the countries more intensively affected by COVID-19.[14] As Figure 1a shows, the electricity generation in Europe (red line) at the beginning of 2020 followed a similar pattern of those observed in 2016−2019, while a sharp decrease is registered as the number of confirmed COVID-19 cases increased and countries implemented lockdown-like measures. While interannual changes in energy generation and usage might be due to changing seasonal conditions, the observed exceptional changes can be primarily attributed to the imposed restrictions to contain COVID-19 spread. In April

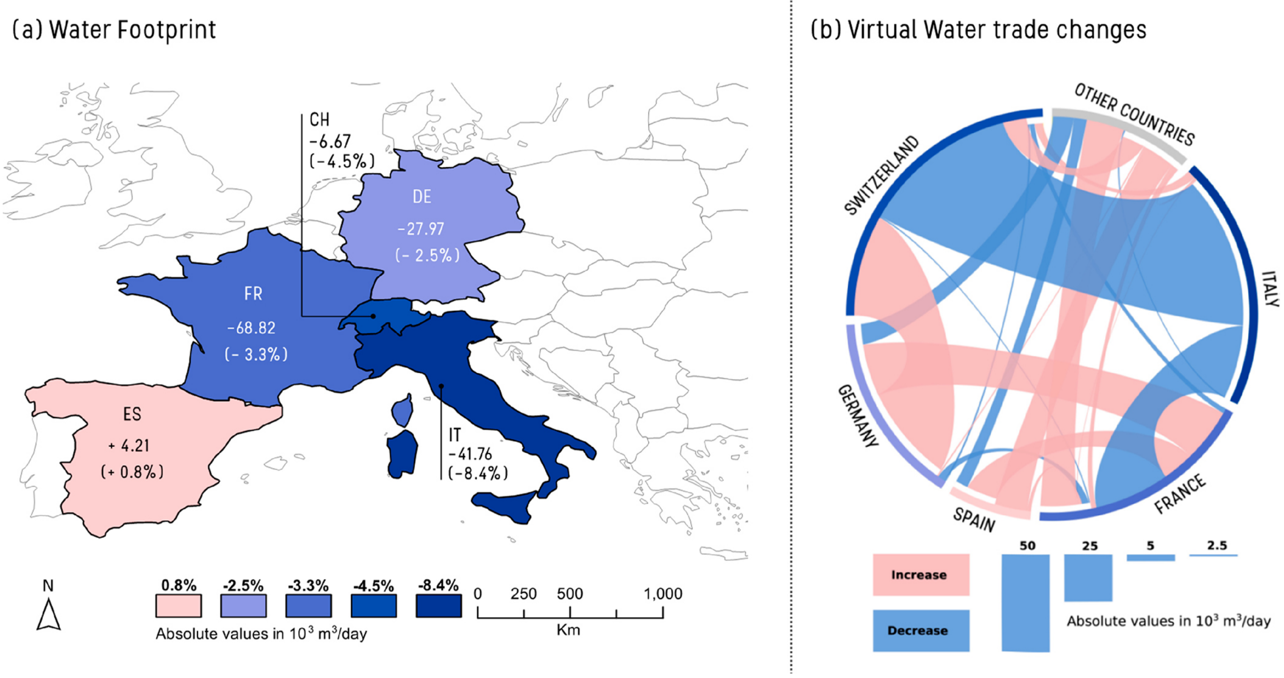

Figure 2. (a) Changes in consumptive water footprint of thermal power plant operations, in 1000 m^3/day and approximate percentage values, across five countries in Europe. Color is proportional to the change in water footprint with respect to the 2016–2019 baseline. (b) Chord diagram with virtual water transfers. Exports from a country are connected to the edge of the plot, while imports have a gap. Consistent with the map on the left, blue shading shows a reduction in virtual water trade and red shading represents an increase. Table S5 in the Supporting Information reports the numeric values used for this figure.

2020, electricity generation in Europe during working days reduced to previous weekend levels, confirming that the decreasing energy demand due to slower economic activity outweighs a possibly increased usage in private homes. This dynamic is also confirmed in the recently published Global Energy Review 2020.[36]

Changes of the Water Footprint in Europe. As a consequence of changing electricity demand, and thus generation, our results show changes of thermal power plant operations in Europe as evident by a lower WF (see blue line in Figure 1b). After March 15, 2020, the consumptive WF of Europe's thermal power plant operations decreased on average by 8.2% compared to the baseline years 2016–2019. We observe that the decline in electricity demand during the COVID-19 pandemic reduced consumption of water resources for electricity generation. Interestingly, the WF was lower than previous years at the beginning of 2020, before the spread of COVID-19 and lockdown-like measures, because the electricity generation has been recently changing to a less water-intensive mix. The share of water-intensive thermal cooling technologies decreased from 68.5% in the baseline years to 62.2% in early 2020 prior to lockdowns and to 61.1% during lockdowns. At the same time, the share of nonwater-consuming technologies (i.e., primarily renewables) increased from 31.5% to 37.8% in early 2020 and to 38.9% during the lockdowns. However, such general figures must be handled with caution. They neither show how the share of different thermal technologies changes (e.g., nuclear) nor do they prove that only an absolute reduction of electricity generation can significantly reduce the water footprint. The Global Energy Review 2020 describes that the increase in renewables is mainly caused by coal and gas being phased out of the electricity mix due to lower demand.[36]

Despite the limitations of these values, our results indicate two critical issues. First, the changing energy mix in the past years has generally reduced the European consumptive WF for thermal power plant operations. However, this change has not necessarily decreased virtual water trade of electricity between countries.[29] Second, the reduction in water footprint during the COVID-19 lockdown-like measures is not only a consequence of a reduced generation but also includes the combined effect of changing generating technologies. Compared to baseline values in 2016–2019, the consumptive WF for thermal power plant operations in Europe has decreased by 21% on average during the lockdowns (equivalent to 1.77×10^6 m^3/day). Of this total reduction, we estimated (eqs S1–S5) that 1.25×10^6 m^3/day was due to changes in the energy mix until 2020 and an additional reduction of 0.52×10^6 m^3/day during the lockdowns (0.23×10^6 m^3/day from the changing energy mix during lockdown and 0.29×10^6 m^3/day from lower electricity demand).

Changes in European resident behaviors due to lockdown-like restrictions and technological changes in electricity generation almost equally contribute to the additional WF reduction during the lockdown period. Our results suggest that short-term behavior changes during an emergency situation or under lockdown restrictions contribute to achieving an immediate reduction in the European WF. However, technological changes in electricity generation and shifting energy mixes appear to reduce water resource consumption more in the longer term.

Changes in Virtual Water Trade between COVID-19 Hotspots in Europe. To understand the virtual water dynamics between the five European countries considered in this study, we investigated the shifts in their domestic WF for electricity in combination with the calculated changes of VW transfers due to electricity import and export. Figures S2−S6 illustrate examples of the dynamics of electricity generation, WF, and VW transfers between the five countries. Italy especially shows a decrease in electricity generation and its related WF and a sharp decline in electricity imports and related virtual water transfers.

Our results for all five considered countries are given in Figure 2. First, the map (Figure 2a) shows that the reduction in electricity load during the lockdowns led to a reduced WF in four of the five nations, with France reducing its WF by more than 68,000 m^3/day. However, when considering relative figures, Italy reduced its WF by approximately 8.4%, followed by Switzerland (4.5%), and France (3.3%), and Germany (2.5%), while Spain shows somewhat stable behavior (<1%).

Considering the virtual water trade network (Figure 2b), Italy appears to not only avoid water consumption domestically, but its decrease in electricity imports also avoided water consumption mainly in Switzerland (−47,400 m^3/day import to Italy) and France (−22,800 m^3/day import to Italy). Italy was the only country that reduced its net foreign water consumption during the lockdown, accounting for differences between imports and exports (Figure S2). The other countries, especially Germany and France, increased their VW imports (Figures S4 and S6). Notably, Germany increased the virtual water consumption in France and Switzerland by 16,200 and 30,500 m^3/day, respectively.

■ DISCUSSION AND CONCLUSION

With the results obtained in this analysis, we conclude that the short-term impact of COVID-19 lockdown-like measures on the consumptive WF of thermal power plant operations and virtual water trade in Europe primarily emerges from domestic WF reductions due to decreased electricity generation. In addition to this observed common behavior for all countries considered, Italy reduced its water footprint abroad because it relied less on electricity imports, while under normal operating conditions it has a strong dependence on electricity from Switzerland and France. The changes in VW trades that are visible in this specific case study are due to the highly interconnected structure of the European electric grid. The COVID-19 hotspot countries considered in this study are located in a cluster of neighboring countries; therefore, strict lockdown-like measures (like those implemented in Italy) can significantly influence VW transfers from and to other countries.

In summary, our analysis contributes to improving the understanding of the sensitivity of the electricity−water nexus in the European electric grid to short-term large-scale behavior changes and can be used to inform future demand-management actions during or prior to emergency situations, as well as planning of infrastructural and technological changes to improve the resilience of the European electric grid and reduce its impact on water resources. Other state-of-the-art studies provided a comprehensive overview of the existing water footprint of European electricity and energy generation. Here, we added to these studies by providing knowledge on the short-term changes of water footprint observed during the COVID-19 lockdowns in Europe within our defined scope of consumptive water footprint due to thermal power plant operations. Within this scope, we compared the effects of technological changes (changing electricity mix) with sudden behavior changes (reduced electricity demand due to lockdown-like measures) on water footprint and virtual water transfer. These two components act on different temporal scales, where the first one is driven by a controlled technological process, while the second is more uncertain as it depends on the sum of collective, potentially very heterogeneous, behaviors. This finding suggests that future climate adaptation strategies for improved resilience of coupled water−energy systems should focus on both dimensions. The combined action of both demand-side interventions and a shift toward a less water-intensive electricity mix is needed to reduce pressure on water resources.

On the basis of our scope of investigating the consumptive water footprint of thermal power plant operations during the COVID-19 lockdowns in Europe, we acknowledge that results from future analyses may differ. Conclusions may change if the water footprint of electricity fuel life cycles, the water footprint of hydropower generation, and gray water footprints are included as suitable data become available. More comprehensive and holistic analyses would help derive generalizable assessments on the total influence of the energy mix or energy efficiency improvements on the water footprint of the European electricity grid and its individual countries, also as compared to other socio-economic determinants of electricity demand. Finally, while we only considered total thermal electricity generation and related water footprint values, future studies could investigate how changing economic activities and lifestyles during the COVID-19 lockdowns affected the efficiency of electricity usage in relation, for instance, to economic outputs. One question to be answered in this regard is why some countries studied here actually increased their electricity imports during the lockdowns, while most economic activities slowed down.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.estlett.0c00381.

> Additional remarks on the methodology (temporal changes of water footprint and virtual water in Europe) (eqs S1−S6 and Figure S1), relevant data used for calculations (Tables S1−S5), and results for individual European countries (Figures S2−S6) (PDF)

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Author Contributions

A.C., M.R., C.M.C., and A.S.S. designed the research and developed the paper. M.R. compiled the data and performed the analysis. M.R. and A.C. designed the visual elements of the paper. A.C., C.M.C., and A.S.S. supervised the research. All authors reviewed the manuscript.

Notes

The authors declare no competing financial interest.

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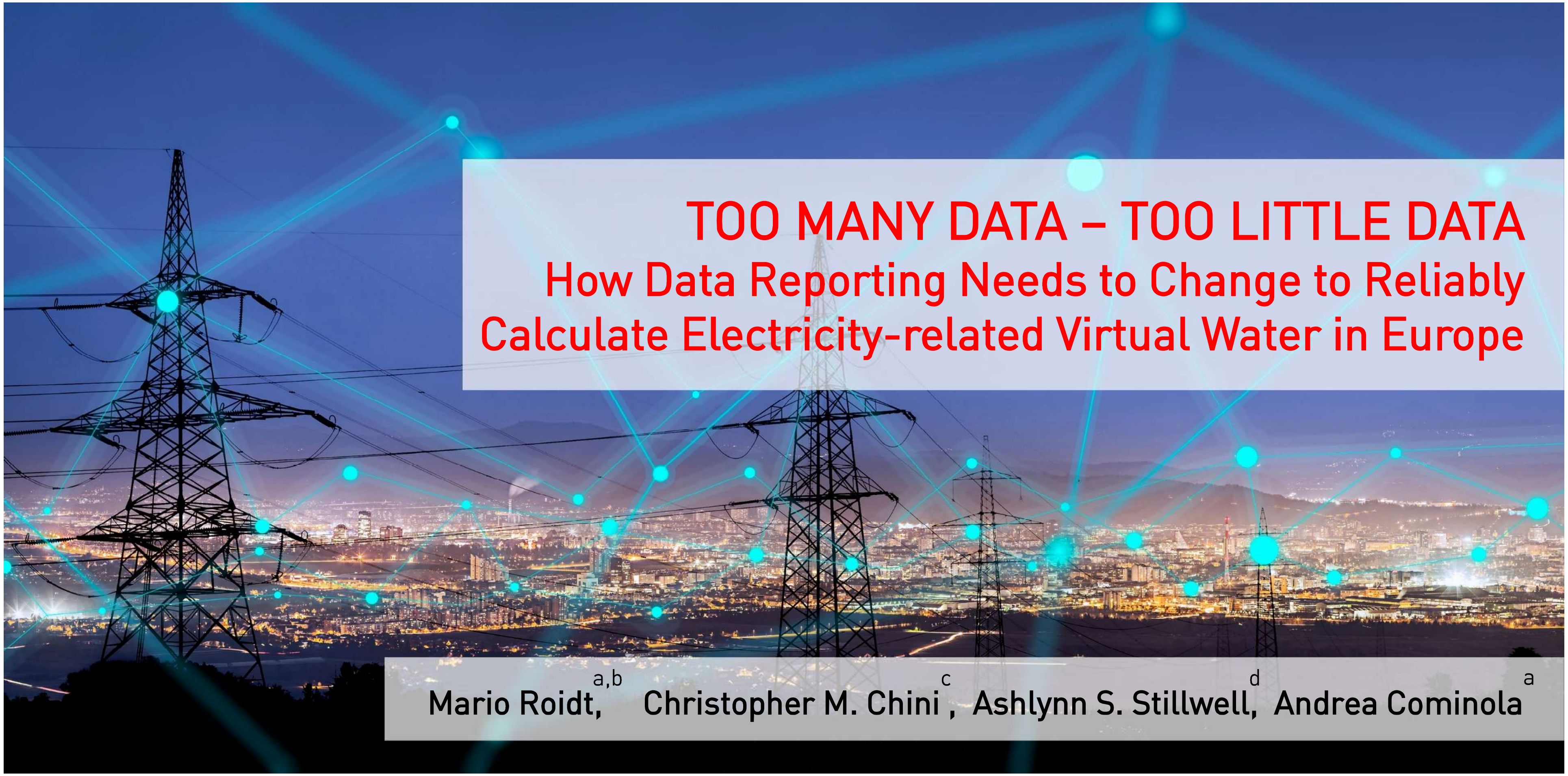
8.7 Publication 8

Too many data – too little data. How data reporting needs to change to reliably calculate electricity-related virtual water in Europe.

M. Roidt, C. M. Chini, A. S. Stillwell, A. Cominola

iEMS Conference 2020, Brussels.



TOO MANY DATA – TOO LITTLE DATA

How Data Reporting Needs to Change to Reliably Calculate Electricity-related Virtual Water in Europe

Mario Roidt[a,b], Christopher M. Chini[c], Ashlynn S. Stillwell[d], Andrea Cominola[a]

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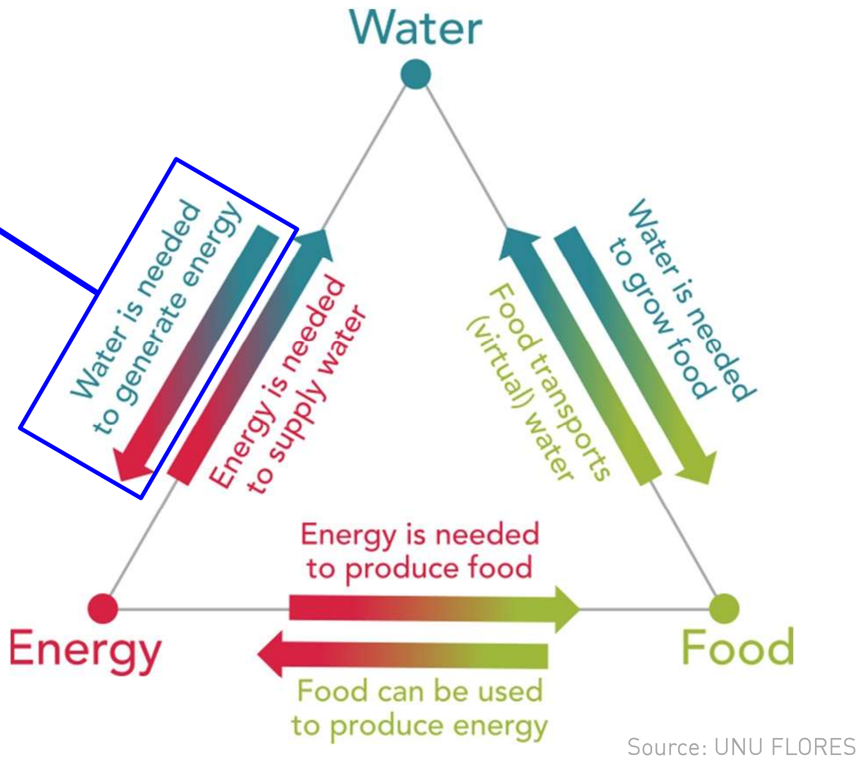
iEMSs Conference 2020
International Environmental Modelling and Software Society
Modelling for Environmental Sustainability (14 -18 September 2020) Brussels, Belgium

The Water-Energy-Food Nexus

Water is needed to generate energy

- Hydropower
- Fossil fuel production and refining
- Water transport of fossil fuels
- Biofuel production
- **Thermo electric cooling**



Source: UNU FLORES

Water Footprint and Virtual Water

Water Footprint

The amount of water consumed to create a product or process

$$WF_{c,d} = \sum_{c,d}^{f} i_f * e_f$$

Water Footprint (m^3)

Water Intensity (m^3/MWh)

Electricity Generation (MWh)

Source: Hoekstra (2012) The Water Footprint Assessment Manual

Source: Mario Roidt

Water Footprint and Virtual Water

Virtual Water

The fraction of the water footprint that is traded (exported)

$$VW_{c,d} = \frac{x}{g} * WF$$

Exported Electricity (MWh)

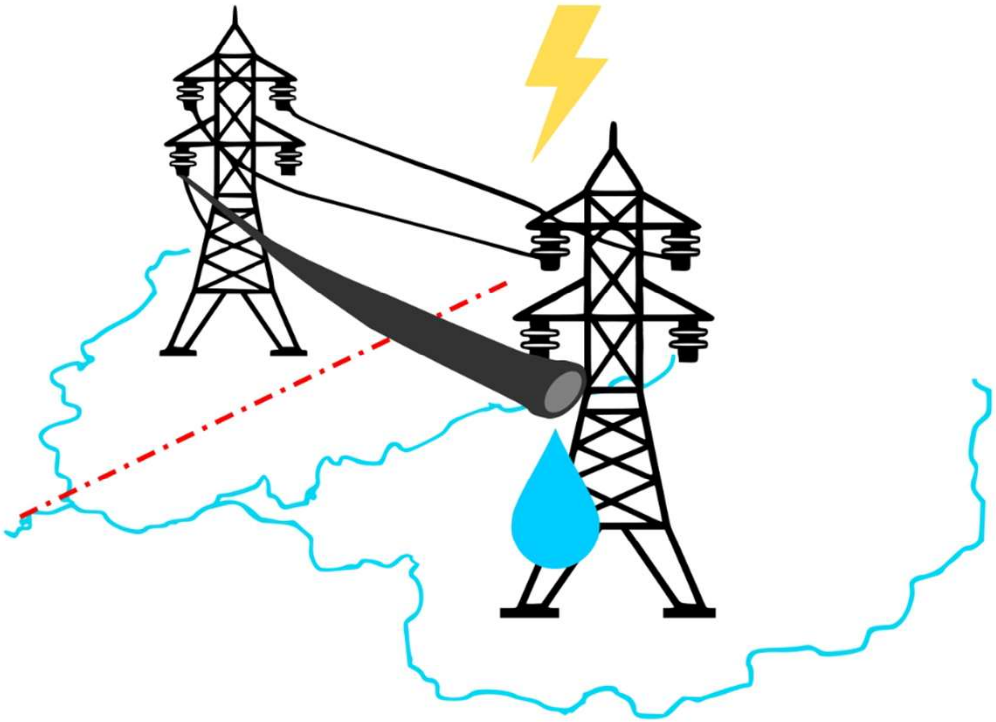
Virtual Water (m^3)

Water Footprint (m^3)

Electricity Generation (MWh)

Source: www.autonews.com

The European electricity grid is transporting virtual water across basin- and country borders



Source: Mario Roidt

Electricity Data for Water Management

In Water-Energy-Food Nexus policy, decision makers must be informed about the electricity sectors´ water footprint and its virtual water trade.

Spatial Scale: Sub-Basin **Temporal Scale: Daily**

Research Questions

1) What is the quality of the data? How complete are available data sets?
2) Are the data available at the right temporal and spatial scale to inform policy makers and water managers?

Research Questions

1) What is the quality of the data? How complete are available data sets?

2) Are the data available at the right temporal and spatial scale to inform policy makers and water managers?

(Too) many data

Transparency Platform
https://transparency.entsoe.eu/

UNIT
Electricity generation at the individual unit (e.g. 2DOE5076X), MWh, <60 min

TYPE
Electricity generation by type (e.g. nuclear) MWh, <60 min

FLOW
Electricity flow between countries (e.g. DE --> IT), MWh, <60 min

Joint Research Centre

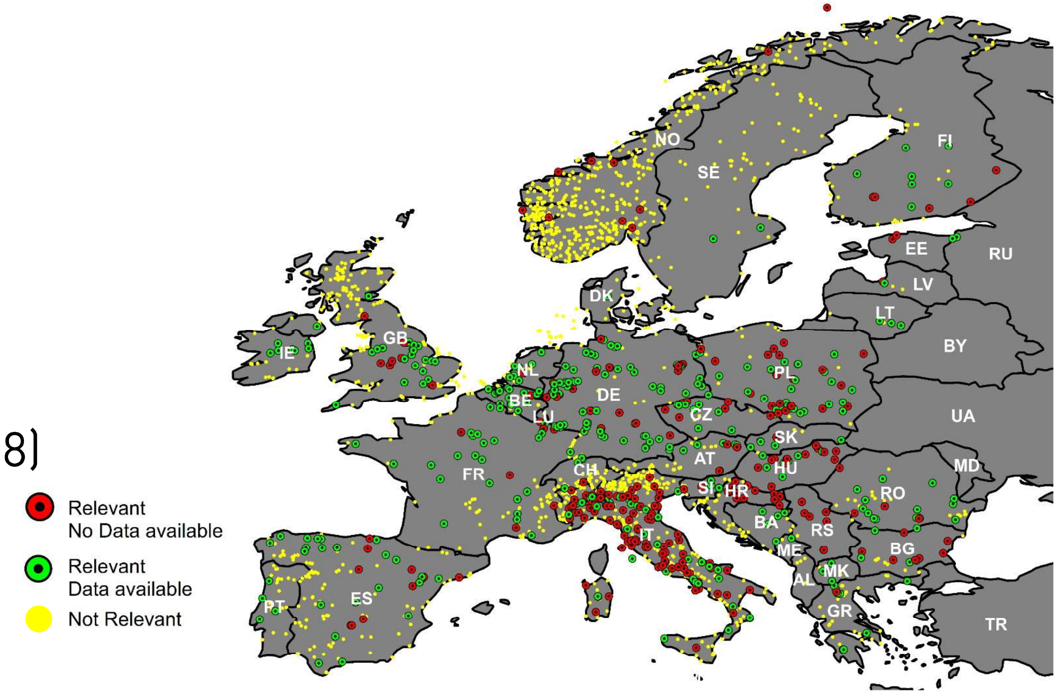
Power Plant Database Open
DOI: 10.2760/5281 (online)

JRC-PPDB-OPEN
European Power Plant Units incl. several metadata
- Identifiers
- Location
- Type
- Status
- Cooling (water intensity)
- etc.

How many power plants provide data?

- 7255 Total Units
  - 5309 Not Relevant
  - 1946 Relevant
    - 1124 Without Data
    - 822 With Data

73% of relevant power plants provide data at high resolution (2018)



Relevant: Thermoelectric power plants; excluding decommissioned plants, seawater cooling and no cooling.

How complete are the data?

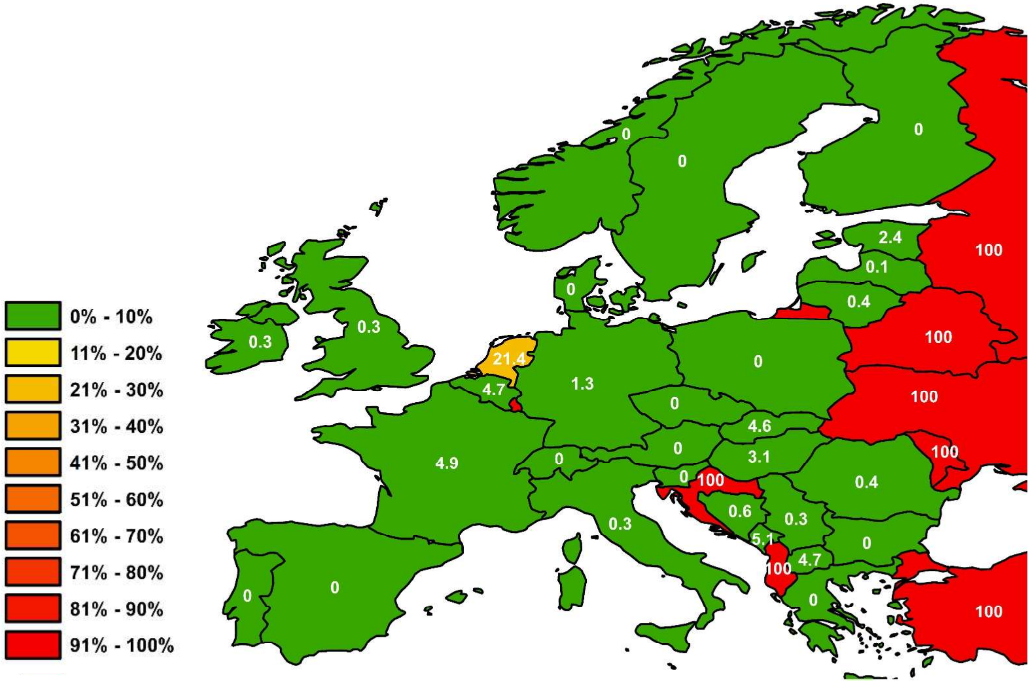
Generation TYPE

Missing datasets in percent

Data accuracy across Europe is high for the TYPE dataset

Several countries have a few percent of missing data

Hirth et al. (2018) conducted similar analysis



See Hirth et al. (2018). The ENTSO-E Transparency Platform – A review of Europe's most ambitious electricity data platform

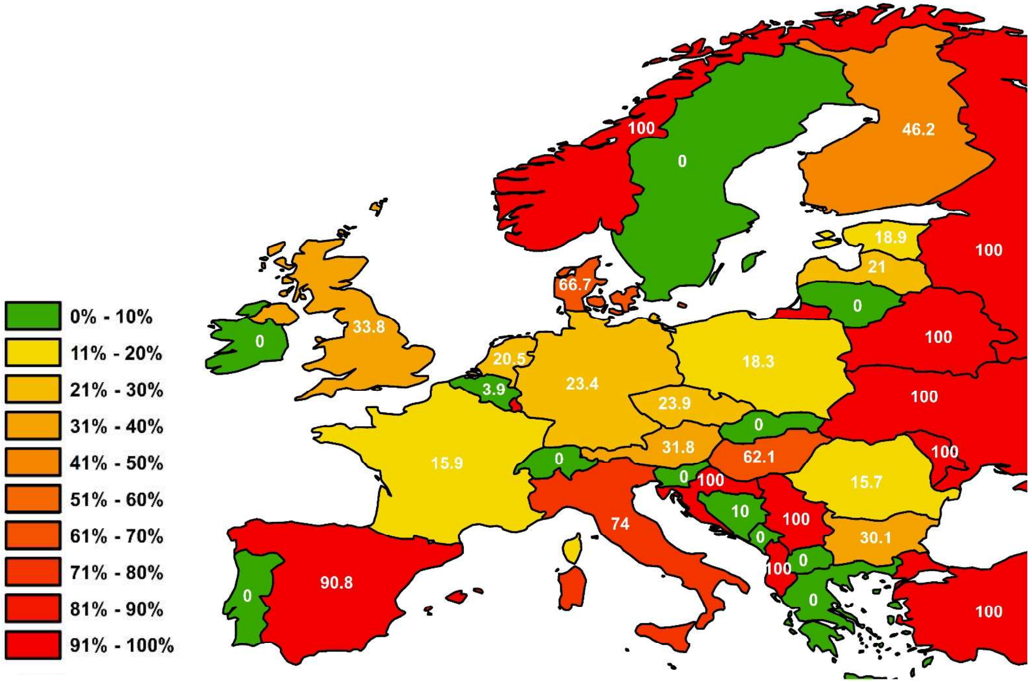
How complete are the data?

Generation UNIT

Missing datasets in percent

Data accuracy across Europe is much lower for the UNIT dataset

Main reason is that not all units provide data



Research Questions

1) What is the quality of the data? How complete are available data sets?
2) Are the data available at the right temporal and spatial scale to inform policy makers and water managers?

Too little data

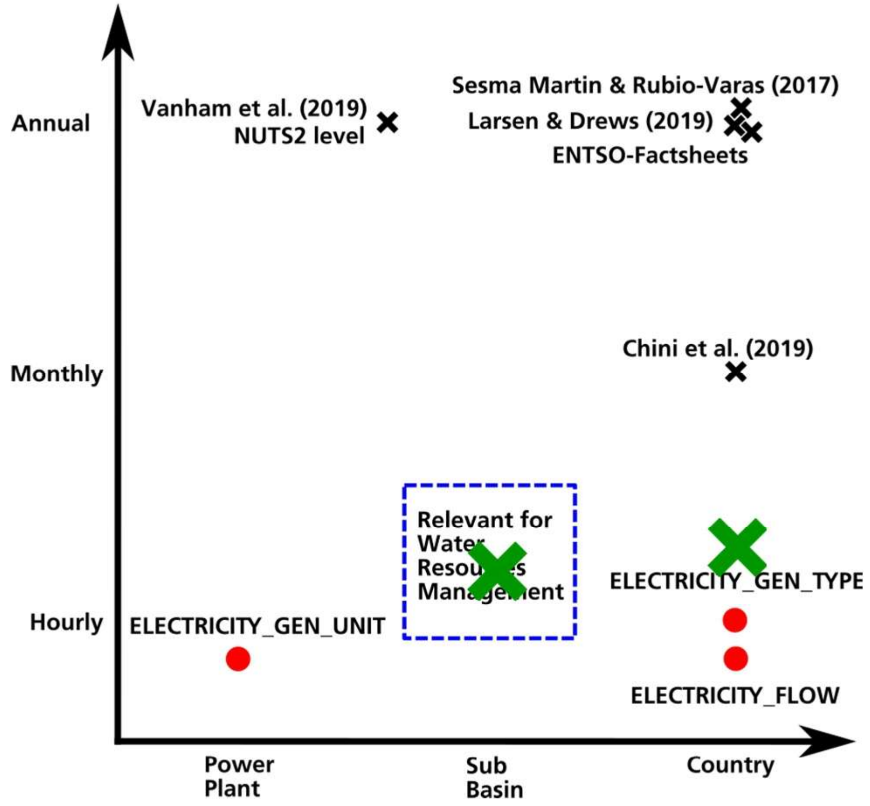
Current literature is mostly at lower resolution

Generation UNIT
Data are incomplete

Aggregation to Sub-Basin is simple

Generation TYPE and FLOW
Data are mostly complete

Disaggregation to Sub-basin is difficult



Example: High Spatial Resolution

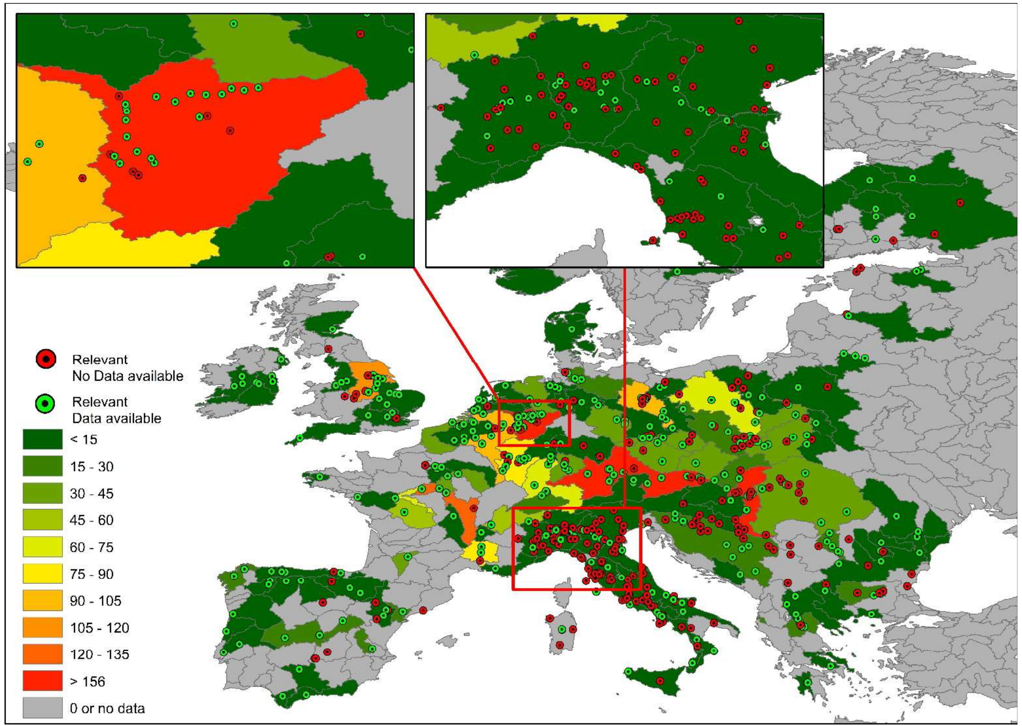
Water Footprint

Time: Annual

Space: Sub-Basin

Sub-Basins with
fewer data underestimate
water footprint

Virtual water
flow between Sub-Basin is not
possible



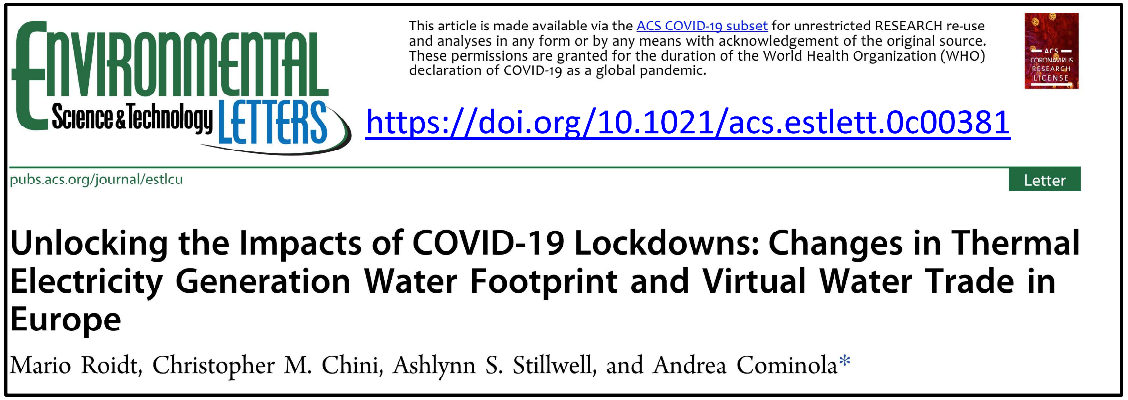
Example: High Temporal Resolution

Electricity

Water Footprint

Time: Daily

Space: Country



ENVIRONMENTAL Science & Technology LETTERS

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pubs.acs.org/journal/estlcu

Letter

Unlocking the Impacts of COVID-19 Lockdowns: Changes in Thermal Electricity Generation Water Footprint and Virtual Water Trade in Europe

Mario Roidt, Christopher M. Chini, Ashlynn S. Stillwell, and Andrea Cominola*

Example: High Temporal Resolution

Electricity Generation and Load in Italy

Seasonal Trend

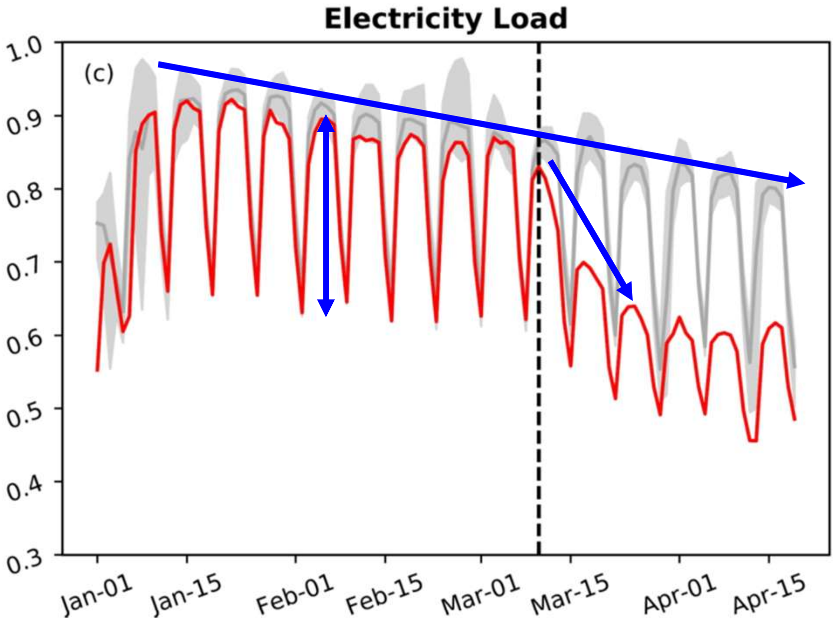
Decrease due to warmer weather

Weekly trend

Strong decrease on weekends
due to industry dynamics

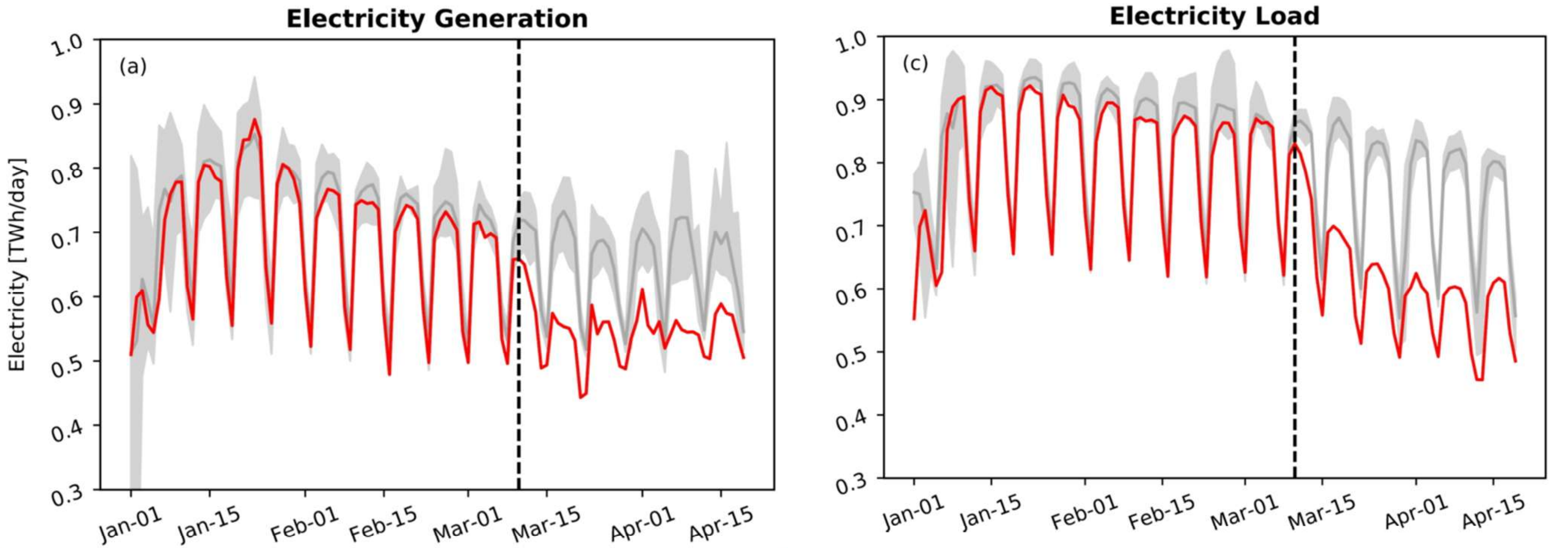
Corona Lockdowns

Decrease to almost weekend
level immediately after lockdown



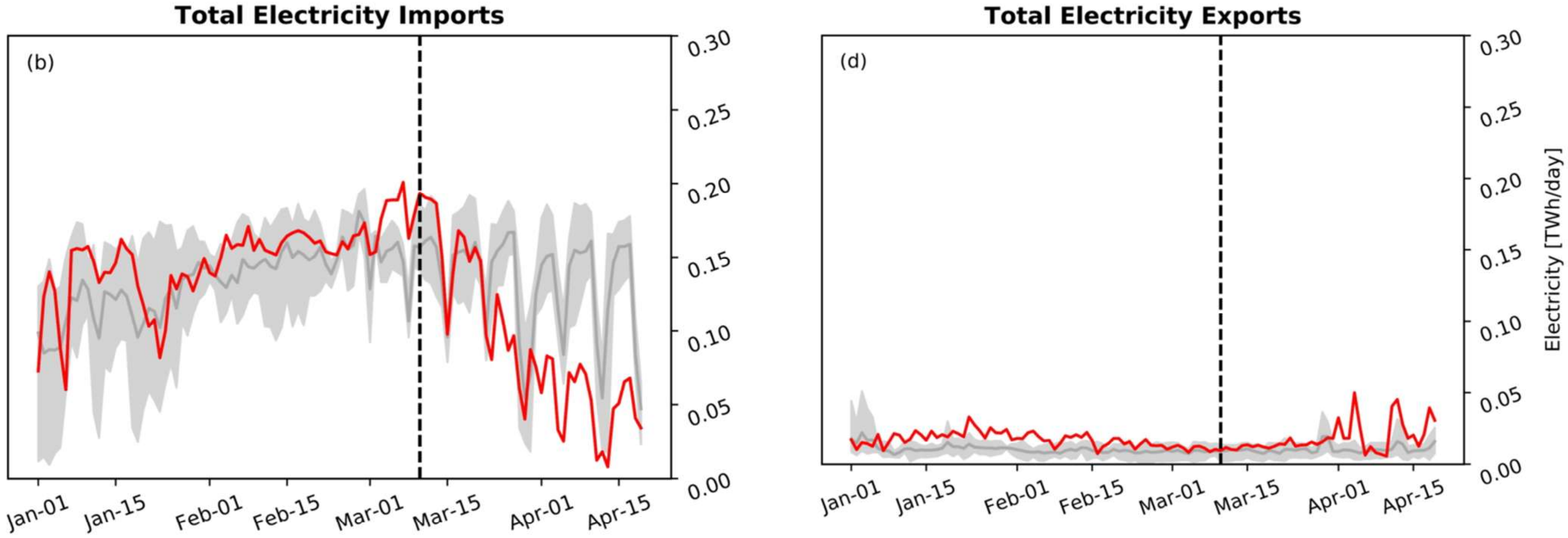
Example: High Temporal Resolution

Electricity Generation and Load in Italy



Example: High Temporal Resolution

Electricity Imports and Exports in Italy



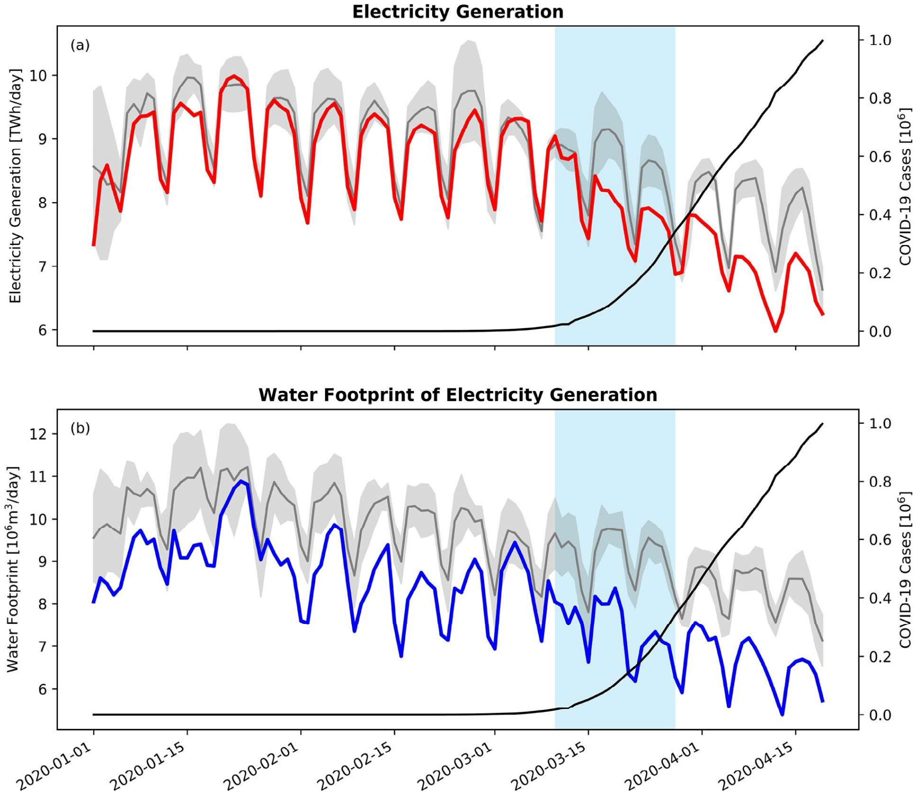
Example: High Temporal Resolution

1.77 Mio m^3/day (21%) decline in water footprint during lockdowns

1.25 Mio m^3/day changing electricity mix between 2016 – 2020

0.23 Mio m^3/day changing electricity mix during lockdown

0.29 Mio m^3/day reduced energy demand during lockdown



Conclusions

- ENTSO-E TP and JRC-PPDB-OPEN lay the foundation for high resolution monitoring of electricity water footprint in European Sub-Basins.
- Continued improvement of data quality of ENTSO-E TP necessary
- More transparency on data quality, reporting and methods of ENTSO-E TP needed (see also Hirth et al. 2018)

Hypothesis

- Completing data availability for all UNITS → Realistic (?)
- Availability of FLOW between Sub-Basins → Unrealistic (?)

Combined Approach for Water Resources Management

1) High resolution water footprint monitoring at the basin scale
2) High resolution virtual water trade between countries

THANK YOU!

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