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Improving water management within the framework of Water 4.0 with a Decentralized Physical Infrastructure Network (DePIN)

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Signed Declaration of Authorship

I hereby declare that the work written and presented in this thesis is entirely my own. Where I have consulted the works of others, this is always clearly stated, with the consulted sources being individually named in the bibliography. The work at hand has not been presented for a degree at any other educational institution. It does not include material that to a substantial extent has been part of any other assignment for the duration of my studies at XU Exponential University and has not yet been published.

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Disclosure Statement

While drafting this manuscript, the author utilized AI (ChatGPT, cursor) for the purpose of grammar and language, structuring, research and coding. The specific material produced by these AI tools within the manuscript is distinctly identified and elaborated in a separate appendix. Before the final submission, the author has meticulously examined the AI-generated content and assumes complete accountability for the contents of the submitted thesis.

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Abstract

This thesis investigates how *Decentralized Physical Infrastructure Networks (DePIN)* can enhance digital transformation and resilience in the water sector within the framework of the *RITS – Resiliente Infrastructure Technology Suit* project. Building on the principles of *Water 4.0*, it explores how decentralized data management, blockchain-based verification, and participatory monitoring can strengthen transparency and collaboration among utilities.

A functional *DePIN Water Prototype* was developed that integrates environmental IoT sensor data with blockchain verification and a web-based dashboard. The prototype demonstrates how real-time water data can be securely collected, validated, and visualized.

The results show that decentralized infrastructures can complement existing systems by improving data trust, operational resilience, and citizen participation. The thesis provides both a conceptual and technical contribution to the RITS vision of resilient, interoperable, and participatory infrastructure systems.

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Chapter 1
Introduction

Water is one of the most essential resources for human societies, ecosystems, and economies. Its reliable provision, efficient use, and sustainable management are among the central challenges of the twenty-first century. Increasing climate variability, demographic change, and rising demands from agriculture, industry, and households are placing unprecedented pressure on water systems worldwide. At the same time, extreme events such as droughts and floods expose the vulnerability of existing infrastructures and underline the urgent need for greater resilience. In Germany, as in many other countries, the water sector faces additional structural difficulties, including aging assets, high energy costs, and a shortage of skilled personnel. Against this background, the modernization of water management has become both a scientific and a societal imperative.

1.1 Problem Statement and Motivation

The German water sector is currently undergoing digital transformation, yet progress remains uneven. While large utilities operate advanced systems for automation and data management, many small and medium-sized providers lack the financial and technical capacity to implement comparable solutions. They often rely on outdated control systems and have no integrated databases, geographic information systems (GIS), or modern monitoring infrastructures. This limits efficiency, hinders interoperability, and restricts evidence-based decision-making (Fricke, Meier & Schmidt, 2019; Krause, Weber & Hoffmann, 2024). At the same time, utilities face growing external pressures: rising energy prices, increasing water demand, and climate-induced stress through droughts and heavy rainfall events. The combination of these factors intensifies the need for adaptable, data-driven management systems that enhance both operational efficiency and resilience.

Beyond these technical aspects, societal expectations are changing. Citizens increasingly demand transparency and opportunities for participation in environmental

governance. Public initiatives that provide real-time access to water-quality or river-level information illustrate how digital tools can strengthen trust and civic engagement (Schreiber, 2024). Digital transformation is thus not merely a question of operational optimization but also of public accountability and participatory governance.
The motivation for this thesis is therefore twofold. First, it seeks to explore the potentials and limitations of digital transformation within the framework of Water 4.0, critically examining initiatives such as W-NET 4.0, which demonstrate how digital tools can support small and medium-sized utilities. Second, it investigates how novel decentralized approaches could complement or even reshape current infrastructure models. The concept of Decentralized Physical Infrastructure Networks (DePIN) offers a promising pathway by combining blockchain technology, the Internet of Things (IoT), and community-driven governance to make critical infrastructures more resilient, efficient, and transparent (Fan, Li & Liu, 2023; Aguilera et al., 2024).
This research is conducted within the framework of the RITS – Resiliente Infrastructure Technology Suit project, which investigates how digital and decentralized technologies can enhance the resilience of critical infrastructures in times of disruption. Within this context, the present thesis contributes a concrete demonstrator for the water sector: a DePIN-based prototype that translates RITS principles—such as decentralization, transparency, and participatory data governance—into a practical implementation for digital water management. The work thereby serves as both a conceptual and a technical contribution to RITS by exploring how decentralized infrastructures can increase adaptability and trust within critical infrastructure systems.

1.2 Research Objective

The overarching objective of this thesis is to investigate how the principles of digital transformation can be advanced in the German water sector by exploring the applicability of Decentralized Physical Infrastructure Networks (DePIN) within the conceptual framework of Water 4.0. While Water 4.0 initiatives such as W-NET 4.0 show how utilities can benefit from digital platforms for monitoring, simulation, and decision support, they remain largely dependent on centralized architectures (Deuerlein et al., 2022). DePIN introduces a fundamentally different logic of infrastructure organization by enabling distributed participation, decentralized data management, and transparent verification through blockchain technologies. These mechanisms have the potential to lower barriers to digital adoption, enhance system resilience, and foster new forms of cooperation among utilities, citizens, and other stakeholders (Ballandies et al., 2023; Fan, Li & Liu, 2023).

Accordingly, the research pursues two main goals: to analyze existing Water 4.0 approaches and identify their limitations with regard to scalability, interoperability, and resilience, and to assess how DePIN concepts can address these shortcomings and provide new opportunities for digital water management. The study follows an exploratory design that combines a systematic literature review with the development of a proof-of-concept prototype. This prototype integrates real-world environmental sensor data, such as those provided by openSenseMap, with a blockchain-based infrastructure for decentralized verification and visualization. By coupling conceptual analysis with practical implementation, the thesis aims to generate findings that are both scientifically sound and empirically demonstrable. The expected outcome is a clearer understanding of how DePIN can serve as a complementary—or potentially transformative—element within the broader Water 4.0 framework.

1.3 Research Questions

To operationalize these objectives, the thesis investigates four central questions that guide both the theoretical discussion and the practical implementation. The first asks what challenges and limitations characterize the digital transformation of the German water sector, particularly among small and medium-sized utilities. The second examines which potentials and shortcomings can be identified in existing Water 4.0 initiatives such as W-NET 4.0, especially regarding scalability, interoperability, and resilience. The third question explores how the principles of Decentralized Physical Infrastructure Networks can contribute to overcoming these shortcomings by promoting distributed sensing, decentralized data management, and new incentive mechanisms. Finally, the fourth question evaluates the opportunities and challenges that arise when translating these conceptual ideas into practice through the implementation of a DePIN-based prototype. Together, these questions form the analytical backbone of the thesis and ensure that both the literature review and the technical development are systematically aligned.

1.4 Structure of the Thesis

The thesis is organized into six chapters that build upon one another to form a coherent argument. Chapter 1 introduces the research context, defines the objectives, and formulates the guiding research questions. Chapter 2 provides the theoretical foundation by examining the digital transformation of the water sector within the framework of Water 4.0. It outlines the status quo of the German water industry, presents key technologies such as the Internet of Things, big-data analytics, digital twins, and geographic information systems, and discusses both their potential and their limitations. The chapter concludes with an in-depth analysis of the W-NET 4.0 project as a representative case study. Chapter 3 shifts the focus to Decentralized Physical Infrastructure Networks, defining the concept, reviewing its technological foundations, and analyzing existing models from other sectors such as energy, communication, and mobility. It then evaluates the transferability of DePIN principles to the water sector through selected use cases. Chapter 4 translates these conceptual insights into practice through the design and implementation of a prototype that integrates environmental sensor data, blockchain verification, and web-based visualization. Chapter 5 discusses and evaluates the results in light of the research questions, compares the prototype with existing digitalization approaches, and outlines future perspectives for DePIN in water management. Finally, Chapter 6 summarizes the key findings, reflects on the contribution to both research and practice, and provides an outlook on future development pathways

Chapter 2
Foundation

The transformation of the water sector towards greater resilience, efficiency, and transparency cannot be understood without first examining its conceptual and technological foundations. This chapter provides the theoretical framework on which the subsequent analysis of decentralized infrastructures builds. It begins by situating the German water sector within the broader dynamics of digital transformation (Section 2.1), highlighting both the current status quo and the transfer of principles from *Industry 4.0* into the water domain.

In this context, *Water 4.0* has emerged as the guiding concept for applying digital and data-driven technologies to water management. It builds on cyber-physical systems, IoT, and automation to connect the physical and digital layers of water infrastructures. Section 2.1 therefore examines three interrelated dimensions: the current situation of the German water sector, the guiding principles and technologies of Water 4.0, and the associated potentials and challenges for implementation (Fricke et al., 2019; Pohl et al., 2018; UBA, 2024).

Section 2.2 then presents *W-NET 4.0* as a practical example that translates these concepts into real applications. By combining GIS, simulation, and data analytics tools, the project demonstrates both the opportunities and the limitations of digital transformation in the water domain.

2.1 Water Management in Digital Transformation

The digital transformation of the water sector is part of a broader global shift toward data-driven and automated infrastructure management. Similar to developments in energy, mobility, and manufacturing, digitalization is reshaping how utilities collect, process, and use information to monitor and optimize their systems. In water management, this transition involves the integration of intelligent sensors, connected devices, and analytical platforms that enable real-time insights and predictive control (Fricke et al., 2019; UBA, 2024).

The concept of *Water 4.0* has emerged as a strategic response to these changes. Derived from the *Industry 4.0* framework, it emphasizes the fusion of physical assets and digital technologies to create smart, adaptive, and interconnected water infrastructures. Water 4.0 seeks to link operational data with strategic decision-making and to enable new forms of collaboration between utilities, regulators, and users (Pohl et al., 2018; Fraunhofer IGB, n.d.). It thus represents both a technological and an organizational transformation of the sector.

2.1.1 Current State of the Water Sector in Germany

Germany's water sector combines high technical standards with a decentralized institutional structure of more than 6,000 mostly municipal utilities. This organization has ensured excellent water quality and service continuity but has also led to heterogeneous technical capacities and varying levels of digital maturity (UBA, 2019; Krause et al., 2024). Many utilities still rely on legacy systems with limited data exchange; although SCADA (Supervisory Control and Data Acquisition) systems are widespread, they are often implemented as isolated solutions, creating fragmented data landscapes that restrict integrated optimization and real-time decision-making (Fricke et al., 2019).

Climate variability, urban growth, and aging assets raise capacity and maintenance demands; leakage rates in some regions exceed 10 percent of total distribution losses (UBA, 2024).

In recent years, utilities have begun adopting smart metering, GIS-based asset management, and digital modeling, but progress remains uneven, especially among small and medium-sized providers. Financial constraints, skill shortages, and uncertain data-governance frameworks continue to limit large-scale digitalization. Nevertheless, the sector's strong technical foundation offers a solid basis for modernization. Digitalization could overcome inefficiencies and strengthen evidence-based planning, provided that data interoperability and cross-sector collaboration improve. These dynamics form the context in which Water 4.0 has emerged—as a framework guiding the transition toward connected, automated, and resilient infrastructures.

2.1.2 Guiding Principles and Key Technologies of Water 4.0

The concept of *Water 4.0* extends the principles of *Industry 4.0* into the water sector, emphasizing connectivity, automation, and data-driven decision-making as foundations for sustainable and efficient water management (Fricke et al., 2019; Pohl et al., 2018). At its core, Water 4.0 promotes the integration of physical systems — such as pumps, valves, and sensors — with digital technologies that enable real-time monitoring, control, and optimization. This fusion of physical and virtual layers transforms traditionally linear water systems into dynamic, adaptive networks capable of responding to changing environmental and operational conditions.

Three guiding principles underpin this transformation.

First, **connectivity** refers to the seamless exchange of data between devices, systems, and stakeholders through standardized interfaces and communication protocols. It ensures that information from distributed sensors and management systems can be shared and utilized efficiently.

Second, **automation** aims to enhance operational efficiency by using smart control systems and algorithms that can autonomously adjust processes such as pressure regulation, treatment, or leakage detection.

Third, **data intelligence** captures the analytical and predictive use of information — applying data mining, machine learning, and simulation tools to support proactive decision-making and long-term planning (Fraunhofer IGB, n.d.; UBA, 2024).

To realize these principles, Water 4.0 relies on a set of **key enabling technologies**:

- **Internet of Things (IoT):** IoT devices form the foundation of digital water networks by collecting and transmitting environmental and operational data from sensors distributed throughout the infrastructure. This allows for continuous system awareness and remote control (Asgari et al., 2022).
- **Big Data and Cloud Computing:** The large volume and heterogeneity of data generated by IoT systems require scalable storage and processing solutions. Cloud-based infrastructures enable central aggregation and advanced analytics for detecting patterns, anomalies, and system inefficiencies (UBA, 2019).
- **Artificial Intelligence (AI):** Machine learning algorithms are increasingly applied for tasks such as demand forecasting, leakage detection, and quality monitoring. AI supports the automation of complex decision processes and facilitates predictive maintenance (Homaei et al., 2025).
- **Geographic Information Systems (GIS):** GIS provides spatial data integration and visualization, which are essential for asset management,

network planning, and risk analysis. It also supports digital collaboration between utilities and municipalities (Radulescu et al., 2023).

- **Digital Twins:** Digital twins represent virtual models of physical infrastructure that enable real-time simulation, optimization, and scenario testing. By linking operational and design data, they support both daily operations and strategic planning (Deuerlein, 2020).

Together, these technologies create the foundation for an integrated and adaptive water-management system. They enable utilities to shift from reactive problem-solving toward predictive and automated control, aligning technical efficiency with sustainability goals. However, their successful implementation depends on overcoming organizational and technical barriers, including data interoperability, cybersecurity, and investment capacity — aspects discussed in the following section.

2.1.3 Potentials and Challenges of Digitalization

The digital transformation of the water sector offers significant potential for improving operational efficiency, transparency, and sustainability. Through continuous monitoring, predictive analytics, and automated control, utilities can optimize energy use, detect leaks earlier, and better manage fluctuating demand. By integrating diverse data sources into unified management systems, digitalization enables a more holistic understanding of infrastructure performance and environmental interactions (UBA, 2024). Moreover, open data and cloud-based collaboration platforms can enhance transparency and facilitate cooperation among utilities, municipalities, and regulators, thereby contributing to improved governance and public trust (Fricke et al., 2019).

Digital technologies also support broader sustainability objectives. Data-driven process optimization reduces water losses, energy consumption, and chemical use in treatment plants, while predictive maintenance extends the lifespan of assets (Krause et al., 2024). Furthermore, digital twins and simulation models provide new tools for long-term infrastructure planning and climate-resilience assessment, aligning digital transformation with the European Green Deal and the United Nations' Sustainable Development Goals (Deuerlein, 2020).

However, realizing these potentials remains challenging. One major barrier is **interoperability** — many utilities operate heterogeneous systems that are not designed for seamless data exchange. Proprietary interfaces, inconsistent data formats, and organizational fragmentation limit the scalability of digital solutions (UBA, 2019). A second challenge is **data governance**: questions of data ownership, access rights, and quality assurance are often unresolved, complicating collaboration between utilities and external partners (Fraunhofer IGB, n.d.).

Cybersecurity has also emerged as a critical concern. As water systems become increasingly connected, they become potential targets for cyberattacks, requiring new strategies for encryption, authentication, and incident management. The lack of specialized expertise further exacerbates this issue, particularly in smaller utilities with limited IT capacity (Krause et al., 2024). In addition, the **financial burden** of modernization remains high, as digital infrastructures demand both capital investment and long-term maintenance resources.

Finally, digitalization is not purely a technical process — it also requires organizational change. The shift toward data-driven management challenges established practices and demands new skills, workflows, and cross-sector cooperation. Successful transformation therefore depends on integrating technical innovation with institutional adaptation and capacity building.

Overall, digitalization holds considerable promise for advancing the sustainability and resilience of the water sector. Yet its successful implementation requires addressing systemic challenges of integration, governance, and security. These factors are exemplified in the following case study, *W-NET 4.0*, which demonstrates how the principles and technologies of Water 4.0 can be applied in practice while revealing the current boundaries of digital transformation.

2.2 W-NET 4.0 as a Case Study

To illustrate the practical implementation of Water 4.0 principles, this section examines the **W-NET 4.0** research and development project, one of Germany's most comprehensive initiatives for digital transformation in water management. The project demonstrates how digital tools and data-driven decision support can strengthen operational efficiency and strategic planning in small and medium-sized utilities — a sector that constitutes the backbone of Germany's decentralized water supply structure (Deuerlein et al., 2022).

Launched under the German Federal Ministry of Education and Research (BMBF) funding program "Smart Water," W-NET 4.0 aimed to create an integrated digital platform that combines simulation, sensor data, and management tools in one coherent system environment (Fraunhofer IOSB, 2023). Its vision was to translate the abstract principles of Water 4.0 — connectivity, automation, and intelligence — into a tangible solution that could be adopted by utilities with limited resources. The project's approach was therefore both technological and institutional: it sought not only to build a robust technical infrastructure but also to develop transferable processes for digital collaboration between research, industry, and public utilities.

2.2.1 Project Goals and Consortium

The overarching goal of W-NET 4.0 was to enable data-driven and simulation-based network management through an open, modular platform architecture. The system was designed to integrate existing data sources — such as GIS databases, SCADA measurements, and asset management systems — and to make this information available for hydraulic modeling, forecasting, and decision support. In doing so, the project aimed to reduce operational inefficiencies, enhance transparency, and strengthen the resilience of water networks (Deuerlein et al., 2022).

Several specific objectives guided the development process:

- **Integration of heterogeneous data** across different software systems to establish a shared information base.
- **Real-time analysis** of network conditions to support preventive maintenance and leakage control.
- **Simulation and scenario modeling** for improved infrastructure planning and emergency preparedness.
- **User-centric visualization tools** to make complex data accessible to operational staff and decision-makers.

To achieve these goals, the project established a diverse consortium that reflected the multi-stakeholder nature of the water sector. Scientific partners such as the Fraunhofer Institute of Optronics, System Technologies and Image Exploitation (IOSB) and the Karlsruhe Institute of Technology (KIT) provided expertise in modeling, sensor technology, and data analytics. Industry partners contributed software solutions for GIS, database management, and web-based visualization, while several municipal utilities served as pilot sites, representing varying network sizes, technical conditions, and levels of digital maturity (Fraunhofer IOSB, 2023).

This collaborative structure ensured that research and practice were tightly interlinked. Utilities provided real-world data and operational requirements, while research institutions translated these needs into modular software components and data interfaces. Continuous feedback cycles allowed for iterative improvement and validation of the platform during development. The result was not a single monolithic system, but rather a *flexible framework* adaptable to the diverse organizational and technical realities of German water utilities.

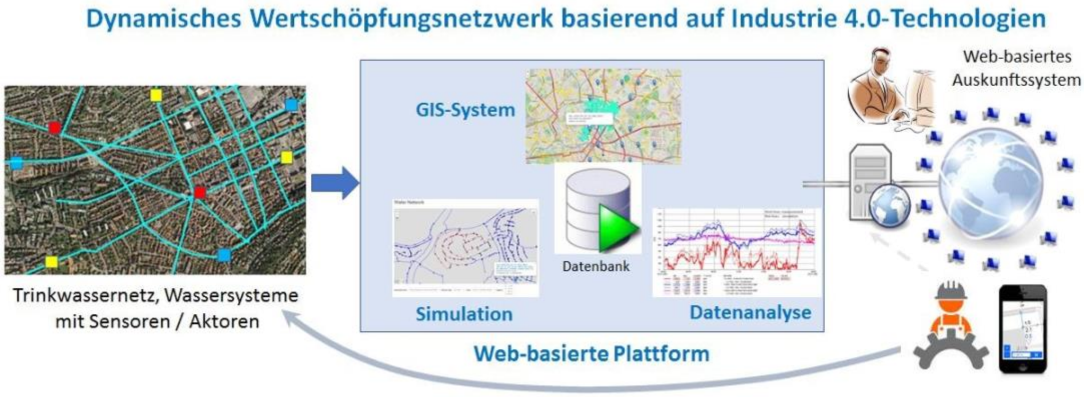

Figure 1 Architecture and data flow in the W-NET 4.0 platform (Fraunhofer IOSB, 2023).

2.2.2 Technical Components

The technical architecture of W-NET 4.0 was designed as an **open and modular ecosystem** that connects previously isolated digital tools—ranging from hydraulic simulations to GIS and monitoring systems—into one coherent platform supporting both daily operations and strategic planning (Fraunhofer IOSB, 2023). The architecture follows a multi-layered design, separating data acquisition, management, and application services to ensure interoperability and scalability.

At the **data-acquisition layer**, information from sensors, SCADA systems, and field reports is standardized into common formats covering parameters such as flow rates, pressure zones, and reservoir levels. IoT devices extend the monitoring capacity, enabling near-real-time data transfer from distributed components.

The **data-management layer** provides the analytical backbone. Geographic Information Systems (GIS) serve as the spatial reference, mapping pipelines and assets in a georeferenced structure that supports advanced spatial queries. Integrated simulation modules calculate hydraulic behavior under different load conditions, facilitating proactive control and scenario analysis. Dashboards and web applications visualize network states and predictive forecasts, while mobile apps synchronize maintenance activities between field and office environments.

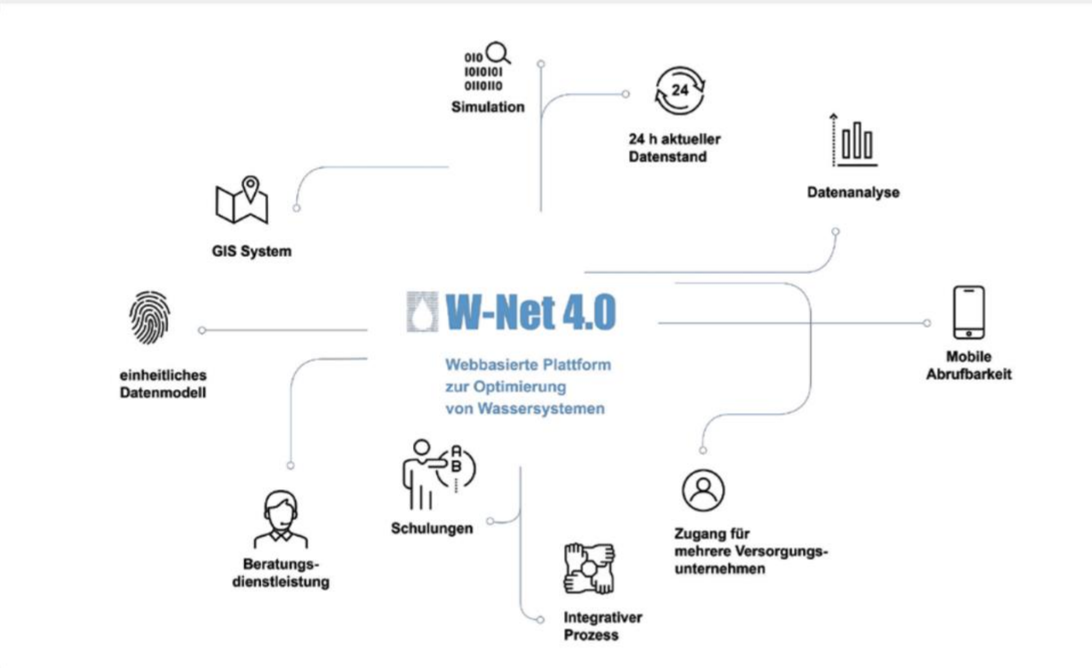

Figure 2 Overview of W-NET 4.0 components and functionalities (Fraunhofer IOSB, 2023).

To demonstrate interoperability, the project relied on **open-source frameworks** such as *GeoServer* and *OpenLayers* for WebGIS visualization, combined with *InfluxDB* and *Grafana* for high-resolution time-series analysis. Mobile applications were designed in accordance with **DVGW guidelines**, ensuring compatibility with industry documentation standards. This technical stack illustrated how small and medium-sized utilities can integrate modern digital tools through standardized interfaces without extensive local IT infrastructure.

By emphasizing modularity and open standards, W-NET 4.0 presented a **pragmatic model** for translating the vision of Water 4.0 into cost-efficient, transferable solutions that accommodate diverse organizational and technical conditions in the German water sector.

2.2.3 Application Scenarios and Results

The W-NET 4.0 platform was evaluated through a series of pilot installations that reflected the diversity of German water utilities—from small rural suppliers to medium-sized municipal networks. These pilots were crucial for testing the system under realistic operating conditions and demonstrating the tangible benefits of digital integration. Each case study focused on specific **application scenarios** derived from the key operational challenges of the sector: network operation, leakage management, firewater supply, and infrastructure planning (Deuerlein et al., 2022).

In **daily network operation**, the integration of real-time sensor data with hydraulic simulation models enabled a continuous comparison between measured and simulated values. Deviations could be identified automatically, allowing operators to detect irregularities such as pressure drops or pump malfunctions at an early stage. The system's capability to visualize flow and pressure dynamics in near real time significantly improved situational awareness, especially in complex networks with multiple pressure zones. This enhanced transparency reduced the reaction time for operational decisions and improved the reliability of supply.

A second focus was **leakage detection**, one of the most economically and ecologically relevant challenges for utilities. By linking SCADA data with statistical anomaly detection algorithms, the platform was able to identify subtle deviations in flow or night-time consumption patterns that may indicate hidden leaks. Pilot utilities reported shorter detection and repair times as well as reduced water losses compared to conventional monitoring approaches. The combination of hydraulic modeling and data analytics proved particularly valuable for distinguishing between sensor errors and actual leaks—an important step toward predictive maintenance.

Another use case addressed **firewater supply and emergency preparedness**. Using the integrated GIS and simulation modules, the platform simulated hydrant performance under various stress scenarios such as peak demand or pipeline closure. The results provided operators and municipalities with evidence-based assessments of firewater availability, supporting both infrastructure planning and compliance with safety regulations (Fraunhofer IOSB, 2023).

In **strategic planning**, the W-NET 4.0 environment served as a decision-support system for asset renewal and network expansion. Through the digital twin functionality, utilities could test alternative investment strategies, evaluate future demand scenarios, and assess the effects of demographic or climatic changes. This planning capability also enabled long-term optimization of energy consumption and pumping efficiency.

Beyond these technical outcomes, the project achieved several **organizational and knowledge-based results**. The cooperative development process strengthened collaboration between utilities and research institutions, fostering digital competence and awareness of data-driven management. Participating utilities reported improved documentation standards, enhanced internal communication, and a clearer understanding of the value of integrated data systems.

Overall, the W-NET 4.0 pilots confirmed that the combination of GIS, simulation, and data analytics can substantially improve transparency, efficiency, and resilience in water management. At the same time, they revealed the dependency of digital innovation on institutional readiness and long-term investment capacity. These insights form the basis for the following analysis of system limitations and lessons learned, which also highlight why alternative and more decentralized infrastructure concepts—such as DePIN—are gaining attention.

2.2.4 Limitations and Lessons Learned

While W-NET 4.0 successfully demonstrated the technical feasibility and benefits of integrated digital water management, the project also exposed several limitations that constrain large-scale implementation. These challenges are not primarily technological but structural and organizational, reflecting the complex realities of the German water sector.

One major limitation concerns **data integration and standardization**. The participating utilities operated heterogeneous legacy systems—ranging from different SCADA configurations to incompatible GIS formats—which complicated data harmonization and synchronization. Even with standardized interfaces, aligning metadata, units, and time resolutions required significant manual effort (Fraunhofer IOSB, 2023). This experience underlines that technological interoperability alone is insufficient without coordinated data governance and consistent national or regional standards.

A second limitation emerged in relation to **organizational capacity and human resources**. Many small and medium-sized utilities lacked dedicated IT departments or data specialists to operate and maintain complex digital infrastructures. The introduction of new software modules often required additional training and adjustments to existing workflows. Consequently, the success of digital transformation proved highly dependent on institutional readiness and long-term personnel development (Krause et al., 2024).

The project also revealed **economic barriers**. Even though modular design reduces entry costs, the cumulative expenses for hardware, software licenses, and maintenance remain substantial. Limited investment budgets, especially in rural utilities, hindered the adoption of advanced analytical tools or continuous sensor networks. Without stable funding models or shared service platforms, the scalability of centralized systems such as W-NET 4.0 remains uncertain (UBA, 2019).

Furthermore, issues of **data security and governance** were identified as critical concerns. The increasing interconnection of operational and cloud-based systems raised questions about data ownership, privacy, and cybersecurity. Utilities expressed hesitation to share operational data across organizational boundaries, fearing misuse or compliance violations. These concerns highlight the need for transparent governance frameworks that clearly define responsibilities and trust mechanisms (Fricke et al., 2019).

Despite these challenges, W-NET 4.0 yielded valuable **lessons for future digitalization efforts**. The project demonstrated that incremental, modular integration—rather than large, monolithic solutions—can effectively support utilities in transitioning toward data-driven operations. It also showed the importance of collaboration between research, industry, and public administration for translating technological innovation into practice.

However, the findings also indicate that centralized digital platforms may reach structural limits when faced with fragmented ownership, distributed infrastructures, and diverse stakeholder needs. Addressing these constraints may require alternative architectures that distribute not only data and computing power but also governance and incentives. The emerging paradigm of Decentralized Physical Infrastructure Networks (DePIN) responds to precisely these challenges by combining digital connectivity with decentralized trust and participation models. This concept, explored in the following chapter, extends the Water 4.0 vision toward a more distributed and resilient digital water ecosystem.

Chapter 3
DePIN in the Context of Water Management

Although the digital transformation of the water sector has advanced under the Water 4.0 framework, most existing systems—such as *W-NET 4.0*—still rely on centralized architectures that limit scalability, transparency, and stakeholder participation (Fraunhofer IOSB, 2023). To overcome these constraints, new approaches based on distributed infrastructures are emerging.

The concept of a **Decentralized Physical Infrastructure Network (DePIN)** links physical assets with blockchain, tokenization, and peer-to-peer technologies to enable collaborative operation, data integrity, and shared ownership (Ballandies et al., 2023). Applied to the water sector, DePIN could complement Water 4.0 by fostering participation, data trust, and resilient digital ecosystems (Asgari et al., 2022).

This chapter introduces the foundations of DePIN (3.1), reviews existing models in other sectors and early water-related initiatives (3.2), and assesses its transferability to the water domain through selected use cases and challenges (3.3).

3.1 Fundamentals and Technological Principles of DePIN

The concept of the Decentralized Physical Infrastructure Network (DePIN) has emerged as a new approach to organizing and operating physical infrastructure systems through decentralized digital coordination. It represents a synthesis of cyber-physical technologies and blockchain-based governance mechanisms that enable infrastructure to be deployed, maintained, and owned collectively rather than by a single central authority. In contrast to the central data platforms characteristic of Water 4.0, DePIN shifts the focus toward *distributed participation, verifiable data integrity,* and *shared resource ownership* (Ballandies et al., 2023).

3.1.1 Definition and Distinction from Traditional Infrastructures

In conventional infrastructures—such as centralized water utilities, power grids, or telecommunications networks—management responsibility, investment, and data ownership are typically concentrated within a single institution or a limited set of operators. These systems depend on hierarchical control structures and closed data environments to ensure stability and regulatory compliance. While this approach guarantees reliability, it also restricts innovation, flexibility, and cross-organizational collaboration (UBA, 2024).

DePIN, by contrast, decentralizes both operation and governance. It connects numerous independent actors—individual users, companies, or institutions—who contribute tangible resources such as sensors, computing nodes, or energy devices. Their participation is coordinated via blockchain-based protocols that verify contributions, allocate rewards, and record transactions transparently (Ballandies et al., 2023; Aguilera et al., 2024). This model replaces institutional trust with *algorithmic trust*, allowing physical infrastructure to function autonomously and transparently without reliance on a central operator.

Three features differentiate DePIN fundamentally from traditional infrastructures:

1. **Distributed Ownership and Participation:** Physical assets are provided by a broad network of contributors, turning infrastructure into a collectively built and maintained resource.
2. **Token-based Incentive Systems:** Economic mechanisms, often realized through blockchain tokens, compensate participants for measurable contributions such as data provision, storage, or maintenance.
3. **Transparency and Verifiability:** All transactions and data interactions are immutably recorded, creating traceable and auditable histories of infrastructure activity.

This shift has profound implications for infrastructure design and governance. Whereas traditional infrastructures optimize efficiency within organizational boundaries, DePIN aims to create *open ecosystems* in which scalability, resilience, and innovation arise from distributed participation. In the context of water management, this principle suggests new ways of organizing monitoring networks, data platforms, and even shared utility services beyond centralized ownership structures.

3.1.2 Technological foundations

The implementation of DePIN relies on the interaction of several technological components that together enable decentralized coordination and transparent data management. These include **blockchain**, **tokenization**, the **Internet of Things (IoT)**, and **distributed storage technologies** such as the InterPlanetary File System (**IPFS**). Each plays a distinct role in translating physical participation into verifiable digital value.

Blockchain technology provides the foundational infrastructure for trustless coordination within a DePIN network. It functions as a distributed ledger in which transactions are recorded across numerous nodes, ensuring immutability and consensus without a central authority. Smart contracts—self-executing code embedded in the blockchain—automate rules for participation, data validation, and reward distribution. In DePIN applications, blockchain guarantees that each contribution, such as data submission or hardware deployment, is verifiable and permanently documented (Ballandies et al., 2023).

Tokenization extends this framework by introducing economic incentives. Contributions to the network—ranging from sensor data provision to storage and energy sharing—are represented as digital tokens that can be earned, exchanged, or used to access network services (Aguilera et al., 2024). These token systems align individual motivation with collective infrastructure development. By attaching measurable economic value to verified contributions, tokenization transforms infrastructure participation into a decentralized marketplace of resources.

The **Internet of Things (IoT)** forms the physical foundation of DePIN networks. IoT devices—sensors, meters, actuators, and gateways—connect the physical world with digital systems, enabling real-time data acquisition and communication. Within a DePIN, IoT devices act as both *data producers* and *verification agents*, providing the input necessary for smart contracts to validate network performance. This integration allows infrastructure systems to become self-reporting and self-regulating (Fan et al., 2023).

To ensure that the large volumes of data generated by IoT devices remain accessible and tamper-resistant, DePIN networks rely on **distributed storage systems** such as IPFS. Unlike centralized cloud architectures, IPFS stores data fragments across multiple nodes, identified by cryptographic hashes rather than physical locations. This approach enhances data persistence, integrity, and censorship resistance (Nododile & Nyirenda, 2025). In combination with blockchain, it enables transparent, verifiable, and scalable data management without reliance on a single server or authority.

Together, these technologies create a cohesive framework for decentralized infrastructure operation. Blockchain ensures trust and governance, tokenization establishes incentives, IoT connects the physical environment, and distributed storage safeguards data integrity. Their convergence enables a new generation of infrastructures that are open, autonomous, and community-driven—an idea further explored through existing sectoral models in the following section.

3.1.3 Typologies of DePIN

DePIN systems can be classified according to their primary function and the type of physical infrastructure they coordinate. While all share the same decentralized governance model, they differ in scope, incentive structure, and technological emphasis. Current developments can be grouped into four main typologies**:** *sensor networks***,** *energy networks***,** *mobility infrastructures***,** and *data and storage systems* (Ballandies et al., 2023).

Sensor networks represent one of the earliest and most accessible forms of DePIN. In these systems, participants deploy IoT devices that collect environmental or infrastructural data, which is then verified and shared via blockchain-based protocols. Networks such as *Helium* and *IoTeX* demonstrate this approach by rewarding users who provide network coverage or sensor data to public registries. Their decentralized structure ensures global data availability without centralized ownership of the underlying infrastructure (Fan et al., 2023).

Energy and resource networks apply DePIN principles to the generation, distribution, and trading of energy. Projects such as *Power Ledger* and the *Brooklyn Microgrid* enable peer-to-peer energy sharing among producers and consumers using token-based accounting systems (Sharples & Fowler, 2021; Power Ledger, 2023). These platforms highlight the potential for decentralized coordination in sectors traditionally dominated by centralized utilities, demonstrating how distributed ownership can enhance flexibility and community participation.

Mobility infrastructures leverage DePIN to coordinate shared resources such as electric vehicle charging stations, vehicle data, or fleet information. Initiatives like *DIMO* and *Share&Charge* use blockchain-based systems to verify and compensate data contributions or charging events, creating transparent mobility ecosystems that bridge individual and institutional users (DIMO, 2023; Share&Charge, 2021).

Finally, **data and storage networks** like *Filecoin* and *Storj* illustrate how decentralized computing and storage resources can replace centralized cloud systems. These networks distribute storage capacity across global participants and use cryptographic proofs to verify data availability and integrity (Protocol Labs, 2021; Storj, 2023). Their success demonstrates the scalability and reliability of decentralized architectures in data-intensive environments.

Emerging research has also begun to explore DePIN concepts in the water sector. Pilot initiatives focus on distributed sensor networks for real-time monitoring of water quality and infrastructure conditions, as well as blockchain-based systems for transparent data sharing between utilities and citizens (Asgari et al., 2022). Although still in their early stages, such projects indicate that DePIN principles—particularly open participation and data verifiability—may complement existing Water 4.0 architectures by overcoming limitations of centralized platforms.

These typologies illustrate the versatility of DePIN across diverse sectors, from digital communication to critical resource management. They also reveal the technological and governance patterns that can inform its adaptation to water management. The next section therefore examines these models in greater detail, comparing their structures, incentive mechanisms, and scalability as a foundation for assessing DePIN's transferability to the water domain.

3.2 Existing DePIN models

Although the DePIN concept is still in its formative phase, several sectors have already demonstrated how decentralized infrastructure can be organized, financed, and governed through blockchain-based systems. These examples provide valuable insights into how participation, incentives, and governance can be structured — and how such approaches might later be adapted to the water domain.

3.2.1 Energy Networks

The energy sector represents one of the most mature application areas for decentralized infrastructure. Projects such as **Power Ledger** and the **Brooklyn Microgrid** exemplify how blockchain and tokenization can enable **peer-to-peer (P2P) energy trading**. In these systems, individual producers (e.g., households with photovoltaic installations) can sell surplus energy directly to local consumers without a central intermediary (Sharples & Fowler, 2021; Power Ledger, 2023).

Smart contracts automatically match supply and demand, verify energy production data, and record transactions immutably on the blockchain. This model not only increases local energy efficiency but also fosters community participation and energy autonomy. The key lesson from these projects is that transparent economic incentives can align individual contributions with collective resource optimization — a mechanism potentially transferable to water distribution and reuse networks.

3.2.2 Mobility Networks

Decentralized mobility systems use blockchain-based coordination to manage shared assets such as vehicle data, fleet information, and charging infrastructure. The *DIMO* network, for instance, enables vehicle owners to share sensor data securely and receive token rewards for verified contributions that improve urban mobility models (DIMO, 2023). Similarly, *Share&Charge* uses blockchain to facilitate transparent billing and authentication between electric vehicles and charging stations (Share&Charge, 2021). These models demonstrate the potential of DePIN to coordinate *complex, distributed infrastructures* with multiple independent stakeholders. Their architecture—based on data verification, tokenized incentives, and open access—closely parallels the challenges faced by water utilities in integrating decentralized sensor data and public contributions into existing management systems.

3.2.3 Telecommunications and IoT Networks

The *Helium Network* is a flagship example of a DePIN-based communication infrastructure. It provides wireless network coverage for IoT devices through a globally distributed network of community-operated hotspots. Participants install and maintain network nodes, earning tokens as compensation for verified coverage (Helium Foundation, 2023). Similarly, *IoTeX* extends this approach by integrating blockchain-based verification into IoT devices, ensuring that data collected from sensors are trustworthy and tamper-resistant (Fan et al., 2023).

These networks illustrate how decentralized participation can build large-scale infrastructure that would otherwise require substantial centralized investment. Their emphasis on data integrity, hardware contribution, and automated validation is directly relevant to water management, where reliable sensing and secure data exchange are critical for network monitoring and environmental management.

3.2.4 Data and Storage Networks

The domain of decentralized data storage has advanced rapidly with platforms such as *Filecoin* and *Storj*. In these systems, participants offer unused disk space to store encrypted data fragments distributed across a global network (Protocol Labs, 2021;

Storj, 2023). Cryptographic proofs, such as “Proof of Replication” and “Proof of Space-Time,” verify that data remain securely stored and accessible over time.

This decentralized model ensures resilience against single points of failure, improves data sovereignty, and reduces dependence on centralized cloud providers. For the water sector, such distributed storage concepts could be applied to manage long-term sensor data archives, ensuring both transparency and accessibility across multiple utilities and stakeholders.

3.2.5 Emerging DePIN Applications in the Water Sector

While still at an early stage, initial efforts to apply DePIN principles to water management have begun to emerge. Research by Asgari et al. (2022) proposes the integration of blockchain and IoT for smart water systems, using distributed ledgers to ensure data authenticity and traceability. More recent prototypes explore **community-based sensor networks** for water quality monitoring, where citizens deploy low-cost sensors and contribute data to open platforms verified through decentralized validation mechanisms (Schreiber, 2024; Homaei et al., 2025).

In addition, hybrid blockchain–IPFS architectures have been tested for **secure and scalable smart metering**, allowing water-consumption data to be collected and stored transparently while preserving privacy (Nododile & Nyirenda, 2025). Although these initiatives remain mostly conceptual, they demonstrate the growing interest in decentralized governance and data sharing as part of the next stage of Water 4.0.

These examples across energy, mobility, telecommunications, and water illustrate that DePIN is not a theoretical construct but a **rapidly evolving paradigm** for critical infrastructures. Each sector adapts the principles of participation, verification, and tokenization to its unique operational context — providing the empirical basis for assessing their transferability to water management in the next section.

3.3 Transferability to the Water Sector

The applicability of Decentralized Physical Infrastructure Networks (DePIN) to water management depends on the alignment between sector-specific needs and the structural capabilities of decentralized architectures. While DePIN principles—distributed participation, token-based incentives, and transparent data governance—have proven effective in sectors such as energy or mobility, the water domain presents unique technical, regulatory, and societal characteristics.

This section therefore evaluates how far existing DePIN models can meet the operational and governance demands of water utilities. The goal is to identify both opportunities and limitations for transferring decentralized principles into the context of *Water 4.0*. The analysis begins with a comparison of sectoral requirements and infrastructural conditions before exploring concrete application scenarios in the following subsections.

3.3.1 Comparison: Requirements of the Water Sector vs. Existing DePIN Models

Unlike energy or mobility networks, the water sector operates under strict regulatory oversight and high public accountability. Water infrastructure is considered a **critical service**, where reliability and safety take precedence over market efficiency or user participation. Consequently, any adaptation of DePIN principles must align with technical robustness, regulatory compliance, and long-term data integrity (UBA, 2024).

At a structural level, several **key differences** emerge when comparing water utilities with sectors such as energy or telecommunications:

1. **Physical Inertia and Locality:**
   Water systems are geographically fixed and hydraulically interconnected. Infrastructure such as pipelines, pumps, and reservoirs cannot be easily scaled or redistributed like computing or storage nodes. DePIN mechanisms must therefore operate on the *data layer*—enabling distributed sensing and information management—rather than on the physical redistribution of infrastructure assets.
2. **Data Sensitivity and Governance:**
   Operational and quality data are subject to privacy regulations and often restricted by municipal or regional ownership structures. While blockchain offers transparency, it also raises challenges regarding data confidentiality. Hence, DePIN applications in water must implement **permissioned access models** or **hybrid architectures**, where sensitive data remain local but metadata and validation proofs are shared via the network (Asgari et al., 2022; Nododile & Nyirenda, 2025).
3. **Economic Incentives and Network Participation:**
   In energy or mobility networks, tokenization can directly reward measurable outputs (e.g., kilowatt-hours or kilometers shared). In water systems, however,

public service obligations and non-market pricing mechanisms complicate the introduction of token-based incentives. Alternative incentive models—such as reputation systems, cooperative funding, or data-sharing credits—may be more suitable for municipal and citizen-driven participation (Sharples & Fowler, 2021).

4. **Interoperability and Technical Standards:**
   The water sector faces ongoing challenges in integrating heterogeneous SCADA, GIS, and sensor systems (Fraunhofer IOSB, 2023). DePIN could address this through open, blockchain-verified data interfaces that promote interoperability and traceability. However, achieving consistent standards across utilities remains a precondition for large-scale adoption.
5. **Resilience and Cybersecurity:**
   While decentralized architectures can increase resilience by removing single points of failure, they also introduce new risks associated with distributed attack surfaces and token misuse. Secure consensus mechanisms, identity management, and encryption standards are therefore essential for water-sector DePIN deployments (Homaei et al., 2025).

Despite these challenges, several complementarities exist between Water 4.0 and DePIN. Both aim to enhance *data-driven decision-making*, *automation*, and *transparency*. The main difference lies in the organizational model: Water 4.0 strengthens centralized digital platforms, whereas DePIN opens the infrastructure to broader participation and shared governance.

From a systems perspective, this complementarity suggests a **hybrid future architecture**: centralized utilities continue to ensure regulatory compliance and operational safety, while DePIN-inspired components enable distributed sensing, citizen participation, and transparent data validation. Such a layered integration could represent the next evolution step—**Water 5.0**—combining the efficiency of central coordination with the openness and resilience of decentralized networks.

3.3.2 Potential Use Cases for Water 4.0

The integration of **DePIN principles** into the water sector offers several promising applications that extend existing Water 4.0 approaches toward greater transparency and participation. The following use cases illustrate how decentralized infrastructures could support efficiency, collaboration, and data integrity in water management.

a) Leakage Detection and Water Loss Reduction

Leakage detection remains a central operational challenge, leading to significant water and energy losses. A DePIN-based model could deploy **distributed IoT sensors** managed by multiple stakeholders — utilities, contractors, or citizens — connected through a blockchain-based validation layer. Sensor data on flow or pressure would be immutably logged, allowing anomalies to be detected collaboratively and transparently (Asgari et al., 2022).

Smart contracts could trigger alerts automatically, while token or reputation systems reward validated contributions. This distributed structure complements centralized monitoring and enhances coverage and fault detection at low cost.

b) Resource Sharing Between Utilities

Many small and medium-sized utilities lack access to advanced analytics and simulation tools. Through DePIN, utilities could **share computational and storage resources** on a cooperative basis, verified via blockchain registries similar to those used in decentralized storage networks (Protocol Labs, 2021). Participants contribute resources and receive proportional access or credits, creating a fair, transparent mechanism for shared digital infrastructure. Such models encourage collaboration and data interoperability, aligning with Water 4.0's goal of collective digital transformation (UBA, 2024).

c) Citizen-Based Water Quality Monitoring

Community participation in water monitoring can be strengthened through **citizen-driven sensor networks** supported by decentralized verification. Individuals deploy low-cost sensors to measure parameters such as pH, turbidity, or temperature (Schreiber, 2024). Submitted data are validated through consensus mechanisms and stored in distributed databases, ensuring authenticity and public accessibility. Instead of direct payment, participants may earn data credits or reputation scores, promoting sustained engagement. This approach democratizes environmental monitoring while maintaining scientific reliability and data traceability.

d) Simulation and Network Planning as Shared Infrastructure

Digital twins are essential tools for planning and optimization (Deuerlein, 2020). A DePIN-based model could distribute their computational and data requirements across multiple utilities. Using blockchain for data rights management and IPFS for distributed storage, utilities could contribute anonymized datasets and collectively simulate network behavior or long-term planning scenarios.
Such a framework would create a **collaborative digital twin environment**, enhancing planning capacity without compromising data privacy.

Together, these examples demonstrate how decentralized infrastructures can enhance operational intelligence and stakeholder participation in the water sector. However, their practical realization depends on how far DePIN principles can be reconciled with the technical, regulatory, and organizational conditions of water utilities — a question examined in detail in the following section (3.3.3).

3.3.3 Opportunities and Limitations of DePIN Adaptation in the Water Sector

The adaptation of Decentralized Physical Infrastructure Network (DePIN) principles to the water sector offers significant potential for innovation but is constrained by structural, technical, and institutional factors. To understand the realistic scope of this transformation, it is necessary to differentiate between principles that are **largely transferable** to water-management contexts and those that are **only partially or not directly applicable**. This analytical distinction provides the foundation for evaluating how DePIN can complement the existing Water 4.0 paradigm.

Transferable Principles

Several core concepts of DePIN align closely with the objectives of Water 4.0 and can be integrated into the sector with relatively low institutional friction.

1. **Data Transparency and Traceability:**
   The use of blockchain-based ledgers for recording and verifying sensor data directly supports the Water 4.0 vision of transparent, data-driven management. Immutable records enhance accountability between utilities, regulators, and citizens, reducing the risk of data manipulation and increasing public trust (Asgari et al., 2022).
2. **Distributed Sensing and Participation:**
   DePIN encourages the contribution of data from heterogeneous sources, including community-operated sensors and private monitoring devices. Such distributed sensing can extend spatial coverage and reduce dependency on proprietary monitoring systems—an approach already compatible with open-data initiatives in the German and EU water sectors (UBA, 2024).
3. **Algorithmic Verification and Decentralized Governance:**
   Smart-contract-based validation mechanisms can automate quality control and compliance processes. In hybrid public–private networks, they could serve as transparent arbitration tools, ensuring that operational data meet predefined standards before integration into central systems (Ballandies et al., 2023).

4. **Interoperability via Open Standards:**
   DePIN's emphasis on open, protocol-based data exchange is well aligned with ongoing digitalization strategies such as DVGW-W 1100 and INSPIRE. Blockchain-verified metadata registries could support long-term interoperability among utilities and technology providers (Fraunhofer IOSB, 2023).

Together, these transferable principles indicate that **DePIN can strengthen the informational backbone of Water 4.0**—making data more transparent, verifiable, and participatory without requiring radical changes to physical infrastructure.

Partially Transferable or Non-Transferable Principles

Other DePIN characteristics, however, face considerable barriers within the institutional and regulatory context of water management.

1. **Token-Based Incentive Mechanisms:**
   While tokenization effectively motivates participation in open energy or mobility networks, it conflicts with the non-commercial nature of public water utilities. Pricing and remuneration are strictly regulated, leaving little room for speculative or market-based reward systems. Alternative non-monetary mechanisms—such as cooperative data credits or reputation systems—may be more suitable (Sharples & Fowler, 2021).
2. **Fully Decentralized Governance:**
   Water services are legally defined as critical infrastructure and therefore require clear accountability and hierarchical oversight. Replacing institutional trust entirely with algorithmic trust, as seen in fully decentralized networks, would be incompatible with public-service obligations and safety regulations (UBA, 2024). Governance must therefore remain hybrid, combining decentralized verification with centralized operational control.
3. **Open Data Publication:**
   Although transparency is desirable, raw operational data often contain sensitive information about network topology and security. Unrestricted publication could increase cyber-risk exposure. DePIN applications must therefore implement permissioned or tiered access models where sensitive data remain local and only hashed proofs are shared on-chain (Nododile & Nyirenda, 2025).
4. **Economic and Technical Scalability:**

Operating distributed nodes and maintaining blockchain infrastructure demand resources and expertise that many small utilities lack. Without shared service models or national coordination, the cost of maintaining decentralized components may outweigh short-term benefits (Krause et al., 2024).

These limitations underline that **DePIN cannot be applied to the water sector as a direct one-to-one transfer of models from energy or mobility**. Its success depends on balancing openness and participation with the strict governance and reliability requirements characteristic of public utilities.

Synthesis

Overall, DePIN offers a valuable complement rather than an alternative to Water 4.0. The combination of transparent data verification, distributed sensing, and open interoperability can enhance efficiency and trust. Yet, achieving these benefits requires **hybrid architectures** that preserve institutional accountability while incorporating decentralized validation and collaboration layers. Such integration points toward an emerging paradigm—sometimes referred to as *Water 5.0*—in which centralized management and decentralized data ecosystems coexist within a unified digital-governance framework.

The insights from this theoretical analysis provide the foundation for the subsequent evaluation of practical implementation in Chapter 4 and the reflective discussion in Chapter 5, where the transferability of these principles is revisited in light of the prototype results.

3.3.4 Outlook: Role of DePIN and Digital Twins in Future Smart City and Smart Water Concepts

Building on the identified opportunities and limitations of DePIN adaptation, the convergence of decentralized infrastructures with digital-twin technologies represents a logical next step in the evolution of Water 4.0 toward more adaptive and participatory systems.

While Water 4.0 focuses primarily on centralized digital integration, future water systems are likely to operate within *hybrid architectures* that combine centralized data management with decentralized sensing, validation, and participation mechanisms.

In such a framework, the digital twin serves as the cognitive layer of the water network — integrating real-time operational data, simulations, and predictive models. DePIN, by contrast, provides the **distributed data and governance layer**, ensuring that inputs from diverse actors remain transparent, verifiable, and securely managed. The two technologies thus form a complementary relationship: the digital twin interprets, while DePIN authenticates and distributes (Deuerlein, 2020; Homaei et al., 2025).

This interaction could redefine the way utilities and municipalities manage infrastructure. Imagine a **Smart Water ecosystem** in which utilities maintain central oversight of operations, while citizens, private partners, and sensors contribute verified data to a shared, open infrastructure. This would allow digital twins to evolve continuously, reflecting real-world conditions with unprecedented accuracy.

Figure 3 Possible look of the digital twin, showing measurements and waterflow

At the **Smart City level**, such systems could interconnect with energy, mobility, and environmental monitoring networks through shared DePIN-based infrastructures, creating a broader **Smart Infrastructure Fabric**. Here, decentralized data flows link different urban domains, supporting resource optimization and sustainability goals aligned with the European Green Deal and UN Sustainable Development Goals (UBA, 2024).

For research and practice, this hybrid approach opens new pathways:

- For utilities, it promises data-driven collaboration beyond institutional boundaries.

- For policymakers, it highlights the need for interoperability standards and regulatory frameworks for decentralized infrastructure.
- For developers, it defines a new domain of socio-technical design, combining open participation with operational reliability.

In summary, DePIN can be viewed not as a replacement for existing water-management systems but as a **scalable extension** of Water 4.0. Together with digital twins, it forms the conceptual and technical foundation for the **next generation of Smart Water infrastructures** — more transparent, resilient, and participatory. The following chapter translates these theoretical insights into practice through the design and implementation of a DePIN-based prototype.

Ultimately, the chapter concludes that **hybrid architectures** combining centralized operational control with decentralized data and participation layers represent a realistic pathway toward future **Smart Water ecosystems**. These insights form the conceptual foundation for Chapter 4, which translates the DePIN principles into practice through the design and implementation of a prototype system.

Chapter 4
Concept and Implementation of the DePIN Prototype

This chapter translates the conceptual framework developed in the previous sections into a practical implementation. The prototype demonstrates how *Decentralized Physical Infrastructure Network (DePIN)* principles can be applied to the water sector to improve transparency, reliability, and participation in data-driven management. By connecting environmental sensor data to a blockchain-based verification layer, it illustrates a technical pathway toward more open and trusted digital water infrastructures.

Within the limited scope of a bachelor thesis, the focus lies on the technical architecture and data flow of the system rather than on building a fully developed digital twin. The digital-twin concept is discussed in Chapter 3 as a future extension, while this chapter concentrates on the coding, data handling, and system integration that enable a functional DePIN environment.

The development process follows a logical sequence. Section 4.1 defines the overall objectives and methodological approach that guided the design of the prototype. Section 4.2 explores the technical foundation, describing how the architecture was structured and implemented—from the integration of open environmental sensors and data sources to the blockchain layer, smart contracts, and the web-based visualization. Section 4.3 then details the implementation workflow, including system integration, testing, and validation of the prototype's core functions. Finally, Section 4.4 reflects on the most relevant challenges encountered during development and the lessons derived from them. The repository can be found on GitHub at: https://github.com/Markus799/depin-water/tree/main/.git-broken.

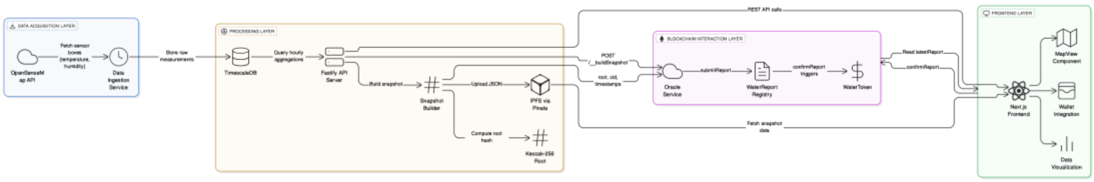

Figure 4 Overview of the DePIN Water prototype architecture showing data acquisition, processing, and blockchain interaction layers.

4.1 Objectives and Methodological Approach

The prototype was developed to demonstrate how the core ideas of *Decentralized Physical Infrastructure Networks (DePIN)* can be translated into a functional technical system for the water sector. Its primary objective is to show how environmental sensor data can be integrated, verified, and shared in a decentralized manner while maintaining data transparency and integrity.

The design process followed a **pragmatic, implementation-oriented methodology** inspired by design science principles. Rather than validating a theoretical model, the focus was placed on constructing and testing an artefact that reflects key DePIN characteristics: distributed participation, verifiable data exchange, and minimal reliance on central authorities.

The development proceeded in several iterative stages. First, the system requirements were defined based on the use cases discussed earlier—such as leakage detection, water-quality monitoring, and inter-utility data sharing. These requirements established the main technical goals: a scalable and modular architecture, a transparent data flow between off-chain and on-chain components, and a simple interface for user interaction.

Second, the software architecture was designed as a **modular containerized system**, enabling separate development and testing of the backend, database, blockchain integration, and frontend. This modularity ensured a clear distinction between the *off-chain* data processing layer and the *on-chain* verification logic.

Finally, the prototype was implemented through an iterative build–test cycle, with each module validated individually before integration. This process supported continuous refinement of data flow, smart-contract logic, and user interaction. The resulting artefact serves as a *proof of concept* that demonstrates both the potential and the practical challenges of applying DePIN concepts to water-management infrastructures.

4.2 Technical Architecture and Implementation

This section describes the technical structure, key components, and data flow of the developed prototype. The system was designed to demonstrate how physical sensor data can be securely transmitted, verified, and published in a decentralized infrastructure using blockchain technology. The architecture follows a modular design to ensure transparency between *off-chain* and *on-chain* operations, which allows each layer of the system—data ingestion, processing, verification, and visualization—to be implemented and evaluated independently.

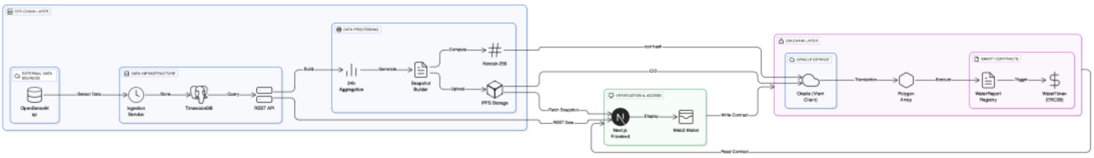

Figure 5 High-level architecture of the DePIN Water prototype showing off-chain and on-chain layers.

4.2.1 System Overview and Design Principles

The prototype was developed as a modular system that demonstrates how decentralized technologies can be applied to water-infrastructure monitoring. Its architecture follows a layered design that separates *off-chain* data handling from *on-chain* verification, ensuring transparency and flexibility in the data flow. Each component—from sensor integration to blockchain interaction and user visualization—operates as an independent module connected through defined interfaces.

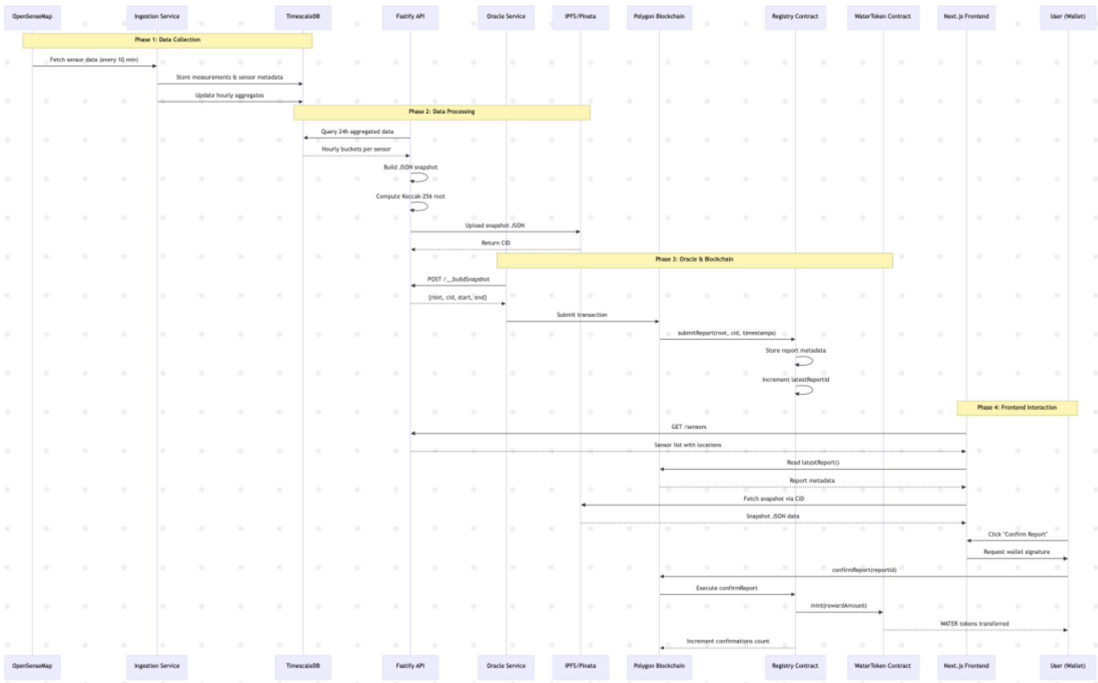

Figure 6 High-level system architecture showing off-chain data collection, oracle communication, blockchain verification, and frontend interaction.

The design was guided by three main principles.

First, **modularity**, which allows each service—backend, database, oracle, blockchain, and frontend—to be deployed, tested, and replaced independently.

Second, **transparency**, ensuring that every data transaction can be traced from its physical source to its verified state on the blockchain.

And third, **scalability**, enabling the system to expand by integrating additional sensors, smart contracts, or analysis layers without major architectural changes.

At the core of this approach is a clear separation between *data acquisition* and *data verification*. Sensor data retrieved from external sources is processed and stored locally before being hashed, published to IPFS, and verified on-chain through smart-contract logic. This workflow mirrors the structure of a typical DePIN environment, where participants collectively contribute to data generation, validation, and governance.

The system was implemented using open-source frameworks and containerized services to ensure reproducibility. *Docker Compose* was used to orchestrate the backend, database, oracle, and frontend, allowing consistent deployment across different environments. This setup provides a robust foundation for experimentation and further development, while keeping the prototype lightweight enough for demonstration purposes within the scope of a bachelor project.

4.2.2 Data Sources and Sensor Integration.

The prototype uses environmental data from *openSenseMap* as its primary input source. *openSenseMap* is an open citizen-science platform that provides real-time environmental sensor data through a public REST API. It represents an ideal data source for this prototype, as it already reflects the distributed and participatory character of a DePIN environment. The platform aggregates thousands of measurements from independent sensors operated by individuals and organizations, covering variables such as air temperature, humidity, and water quality.

Data retrieval is handled automatically through the backend's integration service. The application periodically requests sensor readings using predefined API endpoints that filter by geographic region, sensor type, and data freshness. Each dataset includes a unique sensor identifier, timestamp, location, and measurement value. This structure allows the backend to store and manage the information efficiently in a *TimescaleDB* database, optimized for handling time-series data.

Once retrieved, the data is normalized to ensure consistent units and formats across different sensors. Basic validation routines remove incomplete or outdated entries and verify the presence of all required fields. After preprocessing, the data becomes available for further use within the system—both for visualization and for blockchain verification.

This integration strategy ensures that the prototype operates with realistic and continuously changing environmental data, rather than simulated input. It demonstrates how open data sources can be connected to decentralized infrastructures to improve the transparency and reliability of environmental monitoring. By linking existing public sensor networks with blockchain-based verification, the prototype illustrates a practical step toward open and verifiable Water 4.0 ecosystems.

4.2.3 Backend and Data Processing Layer

The backend forms the central integration point of the prototype, connecting the data source, database, oracle service, and frontend interface. It was implemented using the *Fastify* framework, chosen for its high performance and modular structure, which fits the prototype's goal of demonstrating a lightweight but scalable DePIN system.

The backend retrieves environmental data from *openSenseMap* through scheduled API requests. Each response is parsed and stored in a *PostgreSQL / TimescaleDB* instance that manages the data as time-series entries. This database configuration supports efficient indexing, querying, and aggregation, which are essential for real-time monitoring applications. By maintaining a local database, the system ensures persistence and allows analysis even if the external data source is temporarily unavailable.

Data validation and preprocessing occur within this layer. Incoming datasets are checked for completeness, timestamp consistency, and plausible value ranges. Once validated, they are marked as ready for verification and can be accessed by the oracle service. The backend exposes several REST API endpoints that provide structured access to stored data—for example, retrieving the latest measurement for a specific sensor or listing all unverified records awaiting blockchain submission.

Communication between backend components follows a clear and secure data flow. The oracle periodically queries the API for new validated entries, hashes the corresponding data, and prepares it for on-chain submission. After a blockchain transaction is completed, the backend receives the transaction metadata and stores it alongside the original dataset, maintaining a direct reference between the sensor reading and its blockchain verification.

In addition to managing data exchange, the backend serves as the coordination layer for the overall prototype. It connects the physical data layer with the decentralized verification process and ensures that every piece of information remains consistent across all system components. This modular design also makes it possible to extend the system with additional functionalities, such as data analytics, anomaly detection, or integration with a digital-twin simulation environment in future work.

4.2.4 Blockchain Framework and Smart Contracts

The blockchain framework represents the verification layer of the prototype. Its purpose is to provide a secure and transparent method for validating sensor data, ensuring that each record can be independently traced and confirmed without relying on a central authority. This layer was implemented in *Solidity* and deployed via *Remix* on the *Polygon Amoy* test network, which offers Ethereum compatibility and low transaction costs suitable for experimentation. Interaction with the blockchain occurs through *MetaMask*, which functions both as a wallet and a digital identity provider.

Two smart contracts form the core of this layer. The *WaterReportRegistry* contract handles the registration and verification of sensor reports. Each report submitted by the oracle contains a unique sensor hash, an IPFS content identifier (*cid*), and a timestamp. The contract verifies that each entry is unique before storing it, thereby preventing duplicates and ensuring data integrity. Once published, every record becomes a permanent reference linking the physical measurement to an immutable blockchain entry. The contract also includes a *confirmReport()* function that allows users to verify existing reports directly through their connected wallet, adding an element of participatory validation.

The second contract, *WaterToken*, extends the ERC-20 standard and provides a conceptual incentive mechanism. It represents how tokens could be used in future DePIN-based systems to reward data providers or validators. While the token itself has no economic value in this prototype, it illustrates the potential of integrating incentive models into decentralized infrastructures to strengthen engagement and accountability among participants.

The *viem* client library facilitates communication between the oracle and the blockchain. It manages transaction signing, broadcasting, and confirmation tracking. Once a transaction is confirmed, metadata such as the transaction hash and block number are sent back to the backend and linked to the corresponding data entry in the database. This process closes the verification loop between off-chain and on-chain data.

By combining these elements, the blockchain framework demonstrates a lightweight yet functional implementation of DePIN principles. It shows how sensor data can be secured and validated transparently and how decentralized participation can contribute to data reliability in digital water infrastructures.

4.2.5 Frontend and User Interaction

The frontend provides the interface through which users interact with the decentralized infrastructure. It was developed using *Next.js 15* and designed to translate the technical complexity of blockchain processes into a clear and accessible user experience. The application connects to the blockchain through *wagmi* and *RainbowKit*, enabling secure wallet authentication and transaction handling via *MetaMask*.

The interface visualises live environmental data retrieved from the backend and combines it with the verification state stored on the blockchain. An interactive map built with *Leaflet* displays all active sensors and their locations, along with key measurements such as temperature, humidity, or water quality. Each sensor entry includes metadata on its verification status and a link to the corresponding transaction on the *Polygon Amoy* network, ensuring transparency and traceability.

Users can directly participate in the verification process. By connecting their *MetaMask* wallet, they are able to confirm reports through the *confirmReport()* function of the *WaterReportRegistry* contract. The interface provides real-time transaction feedback, showing the pending, confirmed, or failed state of each operation. This integration allows users to experience the decentralized verification process directly, reinforcing the participatory nature of DePIN systems.

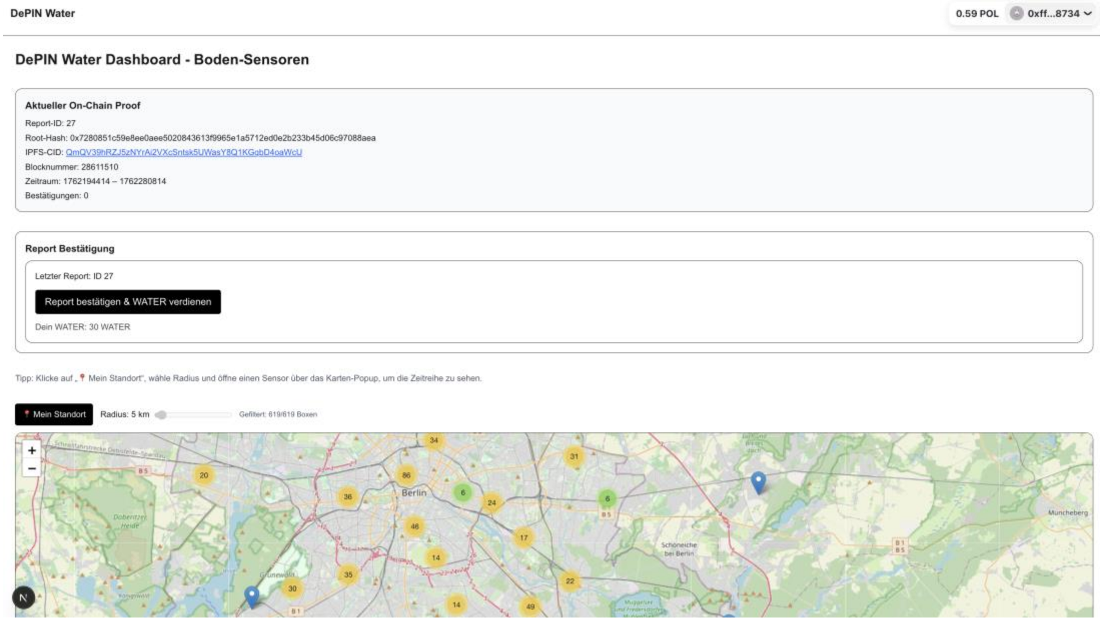

Figure 7 Landing Page Frontend.

In addition to map-based monitoring, the frontend incorporates analytical components implemented with *Recharts*. These visualisations display historical sensor data and trends over time, offering an overview of environmental patterns and system activity. Although simplified, this feature demonstrates how verified data could serve as input for future analytical applications or digital-twin simulations.

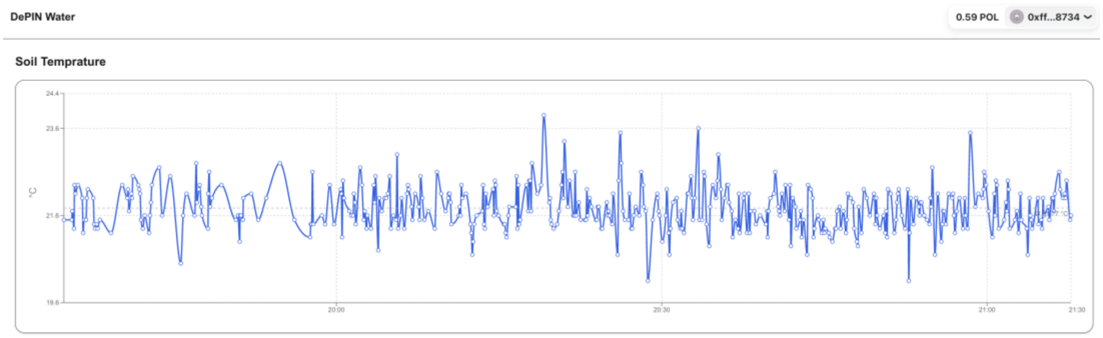

Figure 8 Measurement History Soil Temprature

The frontend thus acts as both a visualization tool and a participation layer. It connects technical verification with human interaction, illustrating how decentralized infrastructures can remain understandable and engaging for end users while maintaining full transparency of underlying data and transactions.

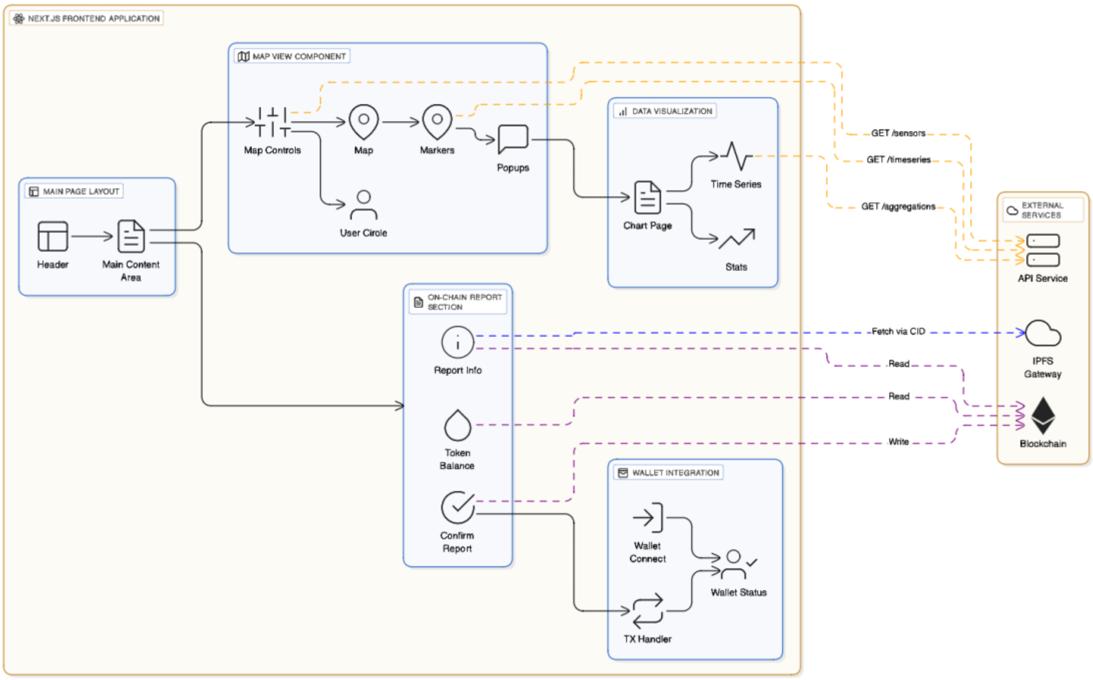

Figure 9 User interface of the DePIN Water prototype showing the map view, data display, and wallet interaction elements.

4.2.6 System Integration, Testing, and Results

All components of the prototype were integrated within a *Docker Compose* environment to ensure consistent deployment and straightforward orchestration of services. The containerized setup includes the backend, database, oracle service, and frontend, each running in a separate container but communicating over a shared internal network. This configuration simplifies testing, guarantees reproducibility, and mirrors the distributed structure of a real DePIN system.

System integration focused on validating the complete data flow—from sensor acquisition to blockchain verification and visualization. Initial tests verified the communication between the backend and *openSenseMap*, confirming that data was retrieved, normalized, and stored correctly in *TimescaleDB*. The oracle service was then tested independently to ensure that data hashing, *IPFS* uploads, and blockchain transactions were executed reliably. Transaction logs and event listeners were used to confirm successful interactions with the *WaterReportRegistry* and *WaterToken* contracts on the *Polygon Amoy* network.

Once the blockchain layer was verified, end-to-end testing was conducted through the frontend. Users could connect their *MetaMask* wallets, view sensor data on the interactive map, and confirm existing reports. Each confirmation created an on-chain transaction, which was displayed in real time and linked to the corresponding record in the database. This interaction confirmed that the system operated as a closed and verifiable loop.

Performance testing showed that the system maintained stable operation under continuous data retrieval and periodic blockchain transactions. The average confirmation time for a transaction on the *Polygon Amoy* network ranged between 10 and 30 seconds, which proved sufficient for demonstration purposes. Minor delays occurred during IPFS uploads, mainly due to network latency, but these did not affect overall system stability.

In summary, the integration and testing phase demonstrated that the prototype successfully achieved its core objective: establishing a transparent and traceable connection between real-world sensor data and a decentralized verification layer. The results confirm the technical feasibility of applying DePIN concepts to water-infrastructure monitoring and provide a stable foundation for the more advanced implementation and evaluation described in the following section.

4.3 Implementation Process

The implementation process followed an iterative, modular approach in which each system component was designed, tested, and refined before full integration. This method ensured stability and allowed for flexible adjustments throughout development. The process combined software-engineering practices such as containerization, automated testing, and continuous refinement with the applied goals of a design-science project.

Development began with the setup of the containerized environment using *Docker Compose*. Each service—backend, database, oracle, and frontend—was defined in a separate container with clear dependencies. This configuration provided a reproducible development environment and simplified deployment. Version control was managed via *Git*, allowing incremental development and testing across modules.

The backend was implemented first, as it served as the system’s core communication layer. Early iterations focused on establishing the connection to *openSenseMap* and ensuring reliable data ingestion. Once the data flow was stable, validation routines and database interactions were added to handle incomplete or inconsistent measurements.

The oracle service was developed next to bridge off-chain data and blockchain logic. After initial trials using mock data, the service was linked to the deployed *WaterReportRegistry* contract. During implementation, attention was given to transaction reliability and gas optimization on the *Polygon Amoy* test network. Several adjustments were made to transaction handling to prevent timeouts and to ensure proper confirmation through the *viem* client library.

The frontend was developed last, combining map-based visualization with blockchain interaction. Initial prototypes focused on displaying live sensor data, followed by the integration of wallet-based user interaction through *wagmi* and *RainbowKit*. Once the full verification loop was operational, design improvements were made to provide clearer feedback on transaction states and verification results.

Testing was performed iteratively across all components. Backend and oracle interactions were verified locally before deployment, and each blockchain transaction was monitored through event logs on the *Polygon Amoy* network. End-to-end tests were conducted via the frontend, simulating typical user interactions such as connecting a wallet, confirming reports, and reviewing verification data. The prototype proved stable under continuous operation and was able to process live data consistently over several testing cycles.

From the development and testing process, several key learnings emerged. The use of a containerized architecture proved essential for maintaining modularity and avoiding dependency conflicts. Integrating real-world sensor data introduced variability that highlighted the importance of robust validation and error handling. Blockchain interaction required careful management of transaction timing and gas costs, even in a test environment, emphasizing the need for efficient oracle design in future implementations. Additionally, direct wallet integration through *MetaMask* demonstrated that user participation in DePIN systems can be intuitive, though proper feedback and interface design are crucial for usability.

Overall, the implementation process confirmed the technical feasibility of combining open environmental data, blockchain verification, and decentralized participation in one coherent prototype. It also provided practical insights into how such systems can be scaled and optimized in future applications.

Chapter 5
Discussion

The previous chapters have outlined the conceptual foundation of decentralized digital infrastructures, examined the transferability of DePIN principles to the water sector, and demonstrated their practical implementation through a prototype system. Building on these results, this chapter discusses the overall findings in relation to the research objectives defined in Chapter 1. It provides an integrative assessment that links the theoretical framework of Water 4.0 and DePIN with the empirical outcomes of the prototype. The discussion begins by revisiting the guiding research questions, followed by a critical evaluation of the prototype, a comparison with existing digitalization approaches, and an exploration of future perspectives for decentralized water management.

5.1 Answering the Research Questions

The guiding research questions formulated in Chapter 1 serve as the analytical backbone of this thesis. Their systematic examination allows for a coherent synthesis of conceptual, methodological, and practical findings. Each question is therefore revisited below and answered based on the insights gained from Chapters 2 to 4.

1. What are the current challenges and limitations in the digital transformation of the German water sector?

The analysis in Chapter 2 has shown that the digital maturity of the German water sector is highly heterogeneous. While larger utilities have established advanced automation and data-management systems, small and medium-sized operators often face significant structural and financial barriers. Legacy SCADA installations, fragmented data landscapes, and the absence of interoperable standards limit integrated optimization and real-time decision-making (Fricke et al., 2019; UBA, 2019; Krause et al., 2024). Furthermore, data governance and cybersecurity remain underdeveloped, with unresolved questions of ownership, access rights, and protection against cyber threats. Beyond these technical aspects, organizational inertia and a shortage of digital expertise impede the adoption of new technologies. The cumulative result is a sector characterized by high reliability but low adaptability. These findings confirm that achieving the Water 4.0 vision requires not only technological innovation but also institutional and regulatory change.

2. Which potentials and shortcomings can be identified in existing Water 4.0 initiatives such as W-NET 4.0 with regard to scalability, interoperability, and resilience?

As examined in Section 2.2, the W-NET 4.0 project demonstrates that digital platforms can substantially enhance transparency, data integration, and operational efficiency. Through the coupling of GIS, simulation, and real-time monitoring, W-NET 4.0 enables more precise control and evidence-based planning, particularly for small utilities. However, the case study also revealed structural constraints that limit large-scale replication. Data heterogeneity, the absence of uniform standards, and a lack of specialized personnel continue to restrict interoperability and long-term sustainability (Fraunhofer IOSB, 2023). Economically, high investment and maintenance costs remain barriers, and institutional fragmentation hampers cross-utility collaboration. Consequently, W-NET 4.0 exemplifies both the promise and the boundaries of centralized digitalization strategies: while technically feasible, they depend heavily on stable governance, funding, and expertise structures that many smaller actors cannot sustain.

3. How can concepts of Decentralized Physical Infrastructure Networks (DePIN) contribute to overcoming these shortcomings?

The theoretical analysis in Chapter 3 suggests that DePIN can complement Water 4.0 by addressing several of its systemic weaknesses. Blockchain-based data verification directly responds to the demand for transparency and trust, while distributed sensor networks extend monitoring capacity beyond institutional boundaries (Asgari et al., 2022). Moreover, open-protocol interoperability aligns with existing standardization efforts in the German water sector. Yet, as Section 3.3.3 clarified, DePIN principles must be adapted to the specific governance and regulatory context of water services. Token-based incentive systems and fully decentralized control structures are incompatible with the public-service mandate of utilities. A hybrid model—combining centralized operational responsibility with decentralized data validation and participation—therefore appears most viable. In this sense, DePIN does not replace

Water 4.0 but rather extends it toward a more participatory and resilient architecture, potentially marking the transition to what might be termed *Water 5.0*.

4. What practical opportunities and challenges arise from implementing a prototype that applies DePIN principles to water management?

The prototype developed in Chapter 4 demonstrates the technical feasibility of integrating real-world environmental sensor data with a blockchain-based verification layer. The results show that sensor readings can be securely transmitted, hashed, and immutably stored on a public test network, ensuring data integrity and traceability. The layered architecture—distinguishing between off-chain processing and on-chain validation—proved effective in maintaining modularity and transparency. User interaction via a web interface and wallet-based confirmation further illustrated the participatory potential of such systems.

However, the implementation also exposed several challenges. True decentralization remains limited, as the oracle service still acts as an intermediary; scalability and performance depend on network latency and transaction costs; and the system requires user literacy in blockchain tools such as MetaMask. These findings confirm that while the DePIN approach can substantially enhance transparency and verifiability, achieving full operational maturity in real-world settings will require improved automation, shared governance mechanisms, and user-friendly interfaces.

In summary, the research questions can be answered as follows: the German water sector faces structural barriers that hinder full digital transformation; Water 4.0 initiatives such as W-NET 4.0 provide important advances but remain centralized and resource-intensive; DePIN offers a promising complementary framework that enhances transparency and participation; and the implemented prototype demonstrates the conceptual feasibility of this integration while revealing the technical and organizational challenges that must still be addressed. These insights form the basis for the subsequent evaluation and comparative discussion in the following sections.

5.2 Evaluation of the Prototype: Functionality, Limitations, and Potential

The prototype developed in Chapter 4 demonstrates how environmental sensor data can be integrated and verified within a decentralized infrastructure. Its evaluation focuses on functionality, limitations, and potential to assess how effectively DePIN principles can be applied to water management.

Functionally, the prototype established a transparent data flow between off-chain and on-chain components. The integration of openSenseMap provided continuously updated sensor data, while the backend managed retrieval, validation, and storage in a TimescaleDB database. The oracle converted validated data into hashed entries, uploaded them to IPFS, and registered corresponding metadata on the Polygon Amoy test network. Each transaction created a verifiable link between physical measurements and blockchain records. The frontend visualized this process intuitively, allowing users to view live data, track verification states, and interact directly via MetaMask. Overall, the system achieved its goal of demonstrating a traceable, participatory verification workflow.

Nonetheless, several limitations emerged. The oracle still functions as a central intermediary, meaning the architecture remains only partially decentralized. Transaction latency and gas fees on the test network limited scalability, while inconsistent API data required manual preprocessing. User interaction through MetaMask, although conceptually valuable, reduced accessibility for non-technical users. These factors highlight that the system serves as an early-stage demonstrator rather than a deployable infrastructure.

Despite these constraints, the results indicate substantial potential. The modular, containerized setup provides a scalable foundation for further development, and the use of open-source components supports reproducibility. By embedding trust and transparency directly into the data flow, the prototype illustrates how decentralized verification can enhance digital water management without relying on central data platforms. Future iterations could distribute oracle functions across multiple nodes, automate validation through smart contracts, and expand sensor integration.

In summary, the prototype successfully translates DePIN principles into a working proof of concept. It verifies the feasibility of decentralized data integrity in the water sector, while its current limitations—particularly in decentralization depth and usability—define clear directions for future refinement.

5.3 Comparison with Existing Approaches

When compared to existing digitalization initiatives such as W-NET 4.0 and international blockchain-IoT projects, the prototype developed in this thesis occupies a distinct position at the intersection of centralized water-management systems and decentralized infrastructure models. W-NET 4.0 represents a mature example of centralized digital transformation, integrating GIS, simulation, and monitoring into a cohesive management platform (Fraunhofer IOSB, 2023). Its strength lies in operational reliability and comprehensive data analysis, yet its complexity and cost restrict adoption among smaller utilities. By contrast, the prototype presented here adopts a lightweight, modular architecture that demonstrates how transparency and verifiability can be achieved without extensive proprietary infrastructure.

In relation to W-NET 4.0, the prototype's contribution lies less in functional breadth than in architectural principle. Whereas W-NET 4.0 aggregates data in central repositories, the DePIN-based system validates data at their point of origin through blockchain hashing and decentralized storage. This approach directly addresses recurring concerns about trust, interoperability, and data ownership identified in earlier projects. While the W-NET 4.0 framework ensures consistency through controlled environments, the prototype illustrates how similar reliability can be supported by distributed verification, thereby reducing dependence on single operators or software vendors. A comparison with international DePIN and blockchain-IoT initiatives further highlights the novelty of the presented approach. Networks such as Helium, IoTeX, or Power Ledger have demonstrated the scalability of decentralized infrastructures in communication and energy sectors (Fan et al., 2023; Sharples & Fowler, 2021). The prototype applies similar principles—tokenizable data contribution, transparent validation, and open access—to the water domain, where regulatory and physical constraints demand more controlled deployment. In doing so, it extends existing DePIN paradigms toward a critical-infrastructure context that prioritizes data integrity over financial incentives.

Overall, the comparison underscores that the prototype does not compete with established systems like W-NET 4.0 but complements them. Its architecture exemplifies how decentralized verification layers could integrate with centralized management platforms to form hybrid Water 4.0 / DePIN ecosystems. Such a combination could unite the robustness and compliance of traditional utilities with the openness and scalability of decentralized networks, offering a realistic pathway toward the envisioned Water 5.0 framework.

5.4 Perspectives and Practical Implications within the RITS Framework

The findings of this thesis point toward a practical transformation of digital water management, where decentralized infrastructures complement existing Water 4.0 systems through demonstrable, real-world applications. Within the framework of the RITS – Resiliente Infrastructure Technology Suit project, the developed prototype functions as a small-scale demonstrator for resilient and interoperable infrastructure. It translates the RITS principles of decentralization, transparency, and trust into a technical solution that can be directly adapted to other infrastructure domains such as energy or mobility.

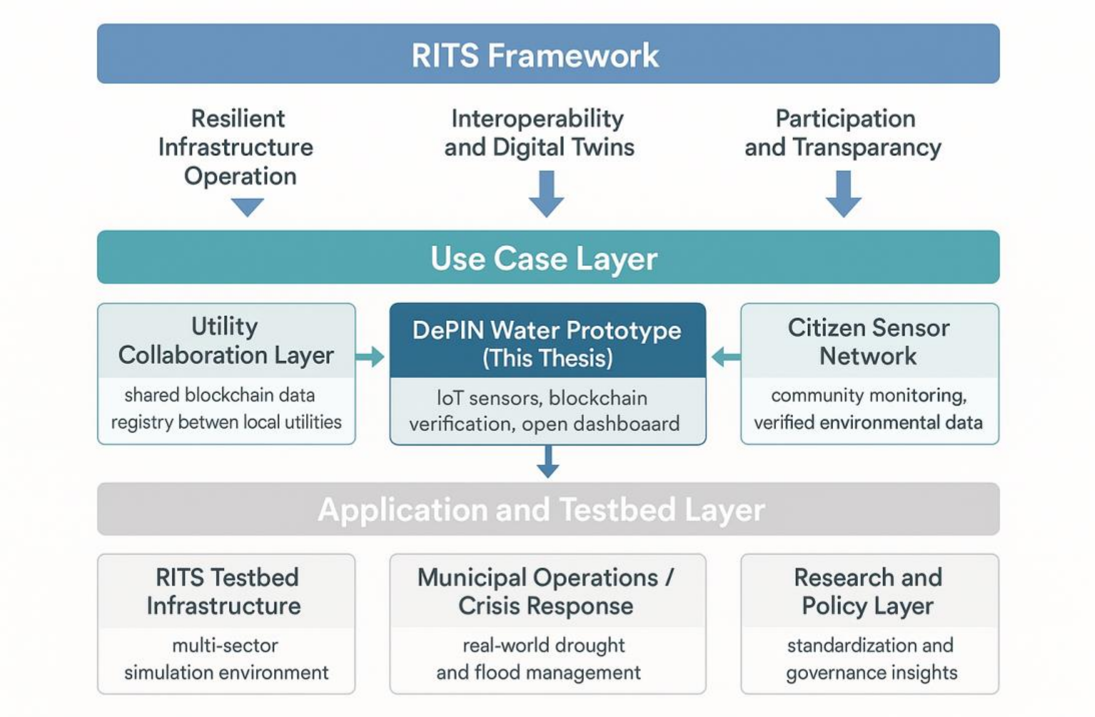

Figure 10 Integration of the DePIN Water Prototype within the RITS – Resiliente Infrastructure Technology Suit framework. The diagram illustrates how the prototype developed in this thesis functions as a practical demonstrator that links RITS objectives—resilienc.

A first practical perspective concerns the integration of DePIN principles with digital-twin environments. In a RITS context, this could mean linking verified real-time sensor data—such as groundwater levels, soil moisture, or reservoir states—to predictive simulation tools operated by utilities or municipalities. For instance, a regional water association could use verified blockchain-stored sensor data to update its digital twin of a distribution network every few minutes, automatically identifying abnormal pressure zones or leakages. Such an implementation would demonstrate how RITS concepts like adaptive modeling and decentralized validation can improve operational awareness and shorten reaction times during crisis scenarios such as droughts or flooding.

A second application perspective lies in inter-utility collaboration and data exchange. Many small and medium-sized water providers lack the capacity for advanced data analytics. Through a DePIN-inspired infrastructure, as explored within RITS, these utilities could share anonymized sensor data in a common blockchain-based registry, accessible to regional partners, environmental agencies, or research institutes. A concrete use case could be a joint monitoring platform for the Brandenburg region, where multiple municipalities contribute data to a shared network that supports drought management and groundwater protection. Smart contracts would ensure that every data input is verifiable and traceable, addressing one of the central RITS goals—trustworthy information flows in distributed systems.

A third, highly practical opportunity is the involvement of citizens and local stakeholders in data collection and monitoring. Community-based sensor networks, for example those deployed along rivers or in agricultural zones, could feed verified data into RITS testbeds. During flood-prone periods, local sensors owned by citizens could complement official monitoring stations, creating a dense, decentralized observation network. The verified information could support real-time decision-making by municipalities or emergency-response units. In this way, RITS' objective of participatory resilience becomes tangible—citizens become active contributors to infrastructure reliability rather than passive recipients of public services.

Figure 11 visualizes how decentralized water monitoring could be implemented within a RITS testbed environment. The image shows distributed IoT sensors, municipal data nodes, and a shared dashboard for real-time water quality and level monitoring.

In addition, the prototype developed in this thesis could serve as a test module within the RITS infrastructure laboratory, supporting experiments on interoperability and governance models. For example, future RITS testbeds could interconnect the DePIN Water prototype with energy or mobility systems to study cascading effects and resilience under simulated stress conditions. This would enable researchers to evaluate not only technical performance but also the institutional implications of decentralized infrastructure governance.

Finally, the broader adoption of decentralized infrastructures will depend on supportive frameworks—technically and politically. Standards for data interfaces, clear governance of blockchain-based data ownership, and lightweight, user-friendly dashboards will be crucial for practical implementation. In RITS, these aspects are being addressed through cross-sector workshops that bring together municipalities, utilities, and technology providers. The prototype presented here could contribute as a reference implementation to these discussions, helping to define best practices for secure and interoperable decentralized infrastructures.

In summary, decentralized infrastructures such as DePIN can make a tangible contribution to the RITS vision of resilient, interoperable, and participatory critical infrastructures. Their potential lies in enabling concrete use cases—from regional sensor collaborations and digital twins to citizen-based monitoring systems—that enhance both transparency and crisis resilience. By grounding theoretical concepts in real-world implementation, this thesis provides a practical foundation for extending RITS research into operational pilot environments and multi-sector applications.

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Chapter 6
Conclusion

The objective of this thesis was to explore how the digital transformation of the water sector can be advanced within the conceptual framework of Water 4.0 by integrating principles of Decentralized Physical Infrastructure Networks (DePIN). Through a combination of theoretical analysis and practical implementation, the research examined whether decentralized architectures can enhance transparency, resilience, and participation in water management. The results show that while Water 4.0 has established a strong foundation for digitalization, its largely centralized systems face structural limitations that DePIN concepts can help to address.

6.1 Summary of Findings

The analysis in Chapter 2 established the current state of digital transformation in the German water sector. Despite high technical standards, many utilities—especially smaller and municipal providers—struggle with fragmented data systems, heterogeneous technologies, and limited resources for modernization. The Water 4.0 framework provides a conceptual response by promoting connectivity, automation, and data intelligence, yet its practical implementation remains constrained by interoperability and governance challenges. The case study of W-NET 4.0 illustrated both the potential and the limitations of current digitalization efforts: integrated platforms can significantly improve operational efficiency and transparency but require substantial institutional and financial capacity.

Chapter 3 introduced DePIN as an emerging paradigm that decentralizes data management and infrastructure participation through blockchain, IoT, and distributed storage technologies. The comparative analysis showed that while DePIN has been successfully applied in energy, mobility, and telecommunications, its adaptation to the water sector must account for specific regulatory and operational requirements. The most promising direction lies in hybrid architectures that combine centralized operational control with decentralized data verification and open participation. Such systems could represent a next evolutionary step—informally referred to as *Water 5.0*—that integrates the reliability of traditional utilities with the transparency and scalability of decentralized networks.

The practical realization of these ideas was demonstrated in Chapter 4 through the development of a prototype. The system successfully connected real-world environmental sensor data to a blockchain-based verification layer, creating a transparent and traceable data flow between off-chain processing and on-chain validation. The prototype confirmed the technical feasibility of decentralized verification and provided an operational framework for testing user participation and data transparency. Its modular, open-source design ensures scalability and reproducibility, making it a valuable foundation for further experimentation.

The discussion in Chapter 5 synthesized these findings. It showed that DePIN can effectively complement Water 4.0 by embedding trust and accountability directly into digital infrastructures. The evaluation of the prototype identified both strengths—such as modularity, transparency, and interoperability—and limitations related to decentralization depth, usability, and scalability. Comparisons with W-NET 4.0 and international DePIN initiatives revealed that the prototype's main contribution lies in its architectural innovation rather than in its functional scope. Future systems could build upon this approach by integrating verified data streams into digital-twin environments and collaborative management platforms.

6.2 Contribution of the Thesis

This thesis contributes to both academic research and practical development in digital water management. Conceptually, it bridges two previously distinct domains—Water 4.0 and decentralized infrastructures—by showing that their integration can yield hybrid architectures capable of enhancing transparency, collaboration, and resilience. Methodologically, the combination of literature analysis and prototype implementation provides a holistic framework for evaluating new digital paradigms. The prototype itself serves as a tangible demonstration of how blockchain technology can be applied to real-world environmental data, translating theoretical principles into operational proof.

For practitioners, the work highlights how open and modular digital systems can support smaller utilities in participating in the digital transformation without relying on large centralized platforms. By using open-source technologies and decentralized verification, the prototype outlines a practical path toward cost-efficient and interoperable solutions. For researchers, the study defines new avenues for investigating hybrid governance models, distributed sensor infrastructures, and data-validation mechanisms in critical-service contexts.

6.3 Outlook: The Future of Water 4.0 and DePIN

Looking ahead, the integration of decentralized principles into water management will depend on both technological and institutional innovation. Technically, future research should focus on enhancing scalability through layer-2 blockchain solutions, improving automation within oracle systems, and connecting verified data with digital-twin and AI-based analytics. Organizationally, success will require clear frameworks for data governance, interoperability standards, and cross-sector collaboration among utilities, regulators, and technology providers.

In the longer term, DePIN-based infrastructures could evolve into participatory digital ecosystems where verified data from utilities, research institutions, and citizens feed into shared planning and monitoring platforms. Such systems would not only improve operational efficiency but also strengthen public trust and environmental accountability. The concept of Water 4.0 would thereby expand beyond technological modernization toward a socio-technical transformation—one that integrates transparency, participation, and resilience as core design principles.

In conclusion, this thesis demonstrates that decentralized infrastructures offer a viable and forward-looking extension of existing digitalization efforts in the water sector. By combining the stability of centralized systems with the openness of decentralized networks, hybrid Water 5.0 architectures can lay the groundwork for more adaptive, trustworthy, and collaborative water management in the years to come.

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Appendix A ChatGPT and Cursor Prompts

This appendix documents selected prompts that were used during the preparation and writing of this thesis. **ChatGPT** served as a supportive research and writing assistant, while **Cursor** was primarily employed for coding, debugging, and technical documentation. Both tools were used to enhance efficiency and ensure clarity, without replacing the author's own analysis, interpretation, or programming work.

ChatGPT supported the structuring of chapters, refinement of language, integration of sources, and visual concept development (e.g., sketches and conceptual diagrams). Cursor assisted in prototype development, including data handling, frontend visualization, and smart contract logic.

A.1 Prompts for Source Integration and Reference Checking

- "Summarize the key findings of this paper and explain how they relate to digital transformation in the water sector."
- "Suggest where this reference could be integrated"
- "Rewrite this paragraph so the in-text citations follow the correct APA style."

A.2 Prompts for Structuring and Content Development

- "Help me design the structure of Chapter 4 (Concept and Implementation of the DePIN Prototype)."
- "Propose logical subsections for describing data sources, blockchain setup, and frontend."
- "Suggest how to transition between the digital twin concept and the DePIN prototype."
- "Generate short captions for my figures and sketches."

A.3 Prompts for Language Refinement and Academic Tone

- "Rephrase this passage to make it sound more academic and precise."
- "Simplify this sentence while keeping it formal and consistent with the thesis style."

- "Improve readability without changing the technical meaning."
- "Ensure the paragraph flows naturally after the previous section."
- "Adjust terminology to maintain consistency with earlier chapters."

A.4 Prompts for Visual and Conceptual Illustrations

- "Create an AI-generated conceptual diagram showing integration of digital twins with DePIN for Smart Water Networks (landscape format)."

A.5 Prompts for Coding and Prototyping (Cursor and ChatGPT)

- "Explain how to connect a Remix smart contract to a test network."
- "Generate a simple frontend snippet for displaying sensor data on a map."
- "Describe how to implement a REST API endpoint for sensor data input."
- "Document the data flow between frontend, blockchain, and backend."
- "Add that the sensor markings are summarized when pulled out."