Harnessing Geosensor Networks for Environmental Decision-Making: Water Management and Renaturation at the Kalterbach, Germany

Master's Thesis

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Master's Programme Land Management and Geospatial Science
TUM School of Engineering and Design

Munich, 31st October, 2023

Technische Universität München

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Master's Thesis submitted to the Technische Universität München, TUM School of Engineering and Design, as partial fulfilment of the requirements for the award of a Master of Science Degree in Land Management and Geospatial Science.

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Declaration

According to § 18 section 9 phrase 1 ADPO (General Study and Examination Regulations for Bachelor's and Master's Degrees) of the Technical University of Munich, I herewith confirm that I have written this thesis entirely by my own and that I did not use any other sources, means of support and aid than those mentioned within the text.

Munich, 31st October, 2023

Your name and signature

Acknowledgments

"The world is full of persons, only some of whom are human, ... life is always lived in relationship to others"

-Graham Harvey

Firstly, I want to express my deep gratitude to the Kalterbach and all the life it supports. I feel privileged for the opportunity to share in their experience of being and for their impressions on my learning. It should should not be taken for granted that this life will always be as rich as it is now. My respect extends to the entire natural system to which the Kalterbach lends only a small contribution. Without our healthy ecosystem, none of this would exist - neither the paper on which these words are printed nor the oxygen which you are breathing to interpret them.

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Abstract

Ecological systems are teeming with intricate dynamics often concealed from human observation. In the past, scientists had to be physically present to gather data, but today, a plethora of advanced technologies enable real-time, remote environmental monitoring. Among these technologies are the Internet of Things (IoT) and Geosensor Networks (GSN), which are poised to revolutionize our understanding and interaction with the natural world. This thesis explores the potential of such technology to enhance environmental decision-making in the case of a renaturation project of the Kalterbach - a stream in the Bavarian countryside, north of Munich. Using an interdisciplinary, participatory approach, a GSN was installed along the water body to record water temperature and water level; a summers worth of remotely and automatically collected data was then analyzed to demonstrate the utility of such systems for environmental monitoring. The results show how various landscape features along the Kalterbach contribute to temperature fluctuations in the stream. Additionally, it explores the correlation between these temperature changes and daily sunshine hours. The valuable insights precipitated from the GSN data help direct the future renaturation of the Kalterbach and thereby underscore the broader promise of IoT in open nature environmental monitoring. The learning from this sensor network were recorded and analyzed to encourage the continued uptake of IoT. While challenges persist, notably in terms of hardware durability, as sensors must endure prolonged exposure to outdoor conditions, if addressed, the technology's affordability and powerful results support its continued use in land management. GSNs provide a scalable interface with ecosystem dynamics that give nature a voice in human systems of governance.

Preface

Where is the greenery in our collective imagination of the future? Why - when we project humanity into the distant tomorrow - do we seem to envision our landscape as barren, inhospitable, and lonely? When did we decide this was our destiny, rather than fight for something better? Somewhere along our inevitable march forward through time, the hopeful glow of a better tomorrow has fallen out of favor for darker dystopias; the flying cars and suave interiors of the Jetsons, the endless possibility and adventure of Star Trek, Star Wars, or Lost in Space, the neon glamor of cyber futures like Tron or Cowboybeep Bop have been replaced with the incessant post-apocalyptic fiction of the Hunger Games, Maze Runner, or Ready Player One (all so readily consumed by us in Gen Z), the ever-growing, late-stage-capitalistic hellscapes of Squid Games, Snowpiercer, even Wall-E, or - to engage with the relevant media of the moment - doomscrolling through irony-soaked tiktoks delivering climate anxiety thinly veiled in self-deprecating humor. And while it is true, a healthy dose of dystopia could be found in all our previous eras' collective consciousness of the future (i.e. Metropolis, Blade Runner, Akira, Soylent Green, Animal Farm, 1984, the Matrix, etc.), it can be hard to ignore the feeling that the scale today has been tilted towards pessimism.

This is not to say our gloom deserves no merit - in fact, at a time like this, I sympathize with the critique that optimism is naive, even vain. The more we've gone looking, the more a sense of dread has reason to grow. We're hurtling white-knuckled and wide-eyed towards self-destruction. The earth has already warmed 1.1 ° C since the mid-19th century benchmark and predictions estimate that even under an intermediate emissions scenario, we can expect to see 3° C of warming by the end of the century [13]. We need not look further than the last few years of wildfires, zoonotic spillover pandemics, the one too many once-in-one-hundred-year flood, crop failures, and continued biodiversity loss to recognize we've turned toward somewhere we'd rather not be going. It is frightening to imagine this is all only the beginning; as the memefied phrase goes "this is not the *hottest* summer on record, it's the *coldest* summer of the *rest* of our lives." And yet, even while looking straight down the barrel of the gun, we appear too paralyzed to do much of anything. We remained oppressively stuck to capitalism, to creaky, corrupt political systems, and seem more bothered to bicker vainly over the problem than to join together and fix it.

Given this hand, it's no wonder for the dark cloud that has settled itself upon our near and distant future - imagining anything else requires a level of effort and creativity that feels out of step with our current trajectory. But even if you take this deluge of critical media to be a sign of an awakening consciousness - a simmering movement ready to critique the status-quo and avert us from the dark home we seem to be building for ourselves - the question remains: if we aren't headed there, where do we go instead? We can't bring forth a better tomorrow if we can't even entertain what that looks like.

Enter Solarpunk. Coined in 2008 by an anonymous blogger (oh so poetically modern), this aesthetic movement envisions a radically different world built on principles of ecology, leveled hierarchy, and justice [25]. It builds on previous punk movements which, while originally stemming from English working class in the 1970s who used music as a social critique, have expanded meaning in the time of the internet with cyberpunk and steampunk being the direct predecessors of this solar iteration. Unlike these earlier forms however, Solarpunk brims with optimism. Solarpunk sees a world where the wealth of our technological developments has been directed for social and environmental good. Crafting a visual language inspired from eclectic sources such as Art Nouveau, the Japanese film studio Studio Ghibli, biomimetics, or lush, reclaimed, biodiverse urban spaces, it imagines a world run on renewables eliminating energy scarcity and where food production is optimized to allow everyone to be fed and healthy. In such a future, people are not forced to work to live, instead they can focus time with one another, on art, passions, self-actualization, on caring for family and friends and the world around them, on kindness [52]. The radical imaginary of Solarpunk provides us a world worth working towards, not just a world to be warned against.

Figure 1: *Artist rendering of a Solarpunk future ; source: screenshot from the animation 'Dear Alice', a project by the animation collective THE LINE[8]*

But what's a thesis on geosensor networks at a rigidly technical university doing spewing these cultural critiques and wading through squishy sociological and art historical literature. For the highbrow engineers and scientists, does this not bruise this work's reputability? What place does this murky world of imagination - taken nonetheless from the chaotically democratic stream of the internet - have in the chrome-like, ivory-tower, objectivity of science? To this, I contend the future can not be brought forward by data alone and I believe it is the responsibility of the scientist and engineer to understand their work in a broader societal context. We do not innovate in a vacuum and therefore it is naive to set technologies out into the world without a consideration to their ultimate destination.

This thesis sees itself contributing to the vision collectively imagined in Solarpunk and imbues the work with all these associated hopes and aspirations. Solarpunk wishes us to live in a world where humanity and nature live in communal understanding - a world where the entire earth is a wild garden and humanity its gardeners - but to arrive at this point we need more than the tools we have today. We must be able to appreciate nature in all its complexity, in real-time, and in sharp focus. Geosensor networks, in addition to other earth observation technologies, provide a means of translating ecological happenings into a human-accessible form. The data from these technologies can help us to identify how our actions as a species impact the world around us and direct us on how we can change to improve outcomes for the benefit of life beyond our own. If Solarpunk is the home we hope to build for our future selves, the technical jargon, mathematics, and informatics of this thesis should be seen as the bricks we lay to actualize that vision.

While reading this thesis, in addition to the primary evaluation on technical and scientific merit, I encourage you to understand all this as connected to a broader web of disciplines, of intentions, and of futures. The Anthropocene has become synonymous with loss, pollution, rampant consumption, and a sickening planet; lets dare to reimagine this relationship and see for ourselves a world of new connection to the many ecologies around us.

List of Acronyms

IoT	Internet of Things
GSN	GeoSensor Network
VDM	Verein Dachauer Moos
WWA	Water Management Office *Wasserwirtschaftsamt*
WFD	European Water Framework Directive
RFID	Radio Frequency Identification
LoWaRAN	Long Range Wide Area Network
MQTT	Message Queuing Telemetry Transport
TTN	The Things Network
CSS	Chirp Spread Spectrum
OGC	Open Geospatial Consortium
API	Application programming interface
FROST	Fraunhofer Open Source SensorThings API
OGC	Open Geospatial Consortium
TUM	Technical University of Munich
LPP	Low Power Payload
PCHIP	Piecewise Cubic Hermite Interpolating Polynomial
SWOT	Strengths Weakness Oppertunities and Threats
ARMA	Auto-regression Moving Average

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1 Introduction

1.1 Problem

As a continent shaped by thousands of years of intensive land use and the birthplace of industrialization, the European landscape continues to experience a state of remarkable natural decline [5]. Along with the ever present challenge of climate change, Europe's nature is threatened by industrial agriculture, land abandonment, and urbanization; habitat crucial for building a resilient, biodiverse landscape have not gotten the support they need to thrive. However, in recent years, alongside the growth of a global environmental consciousness, European governments have begun to comprehend the importance of wild ecologies and a paradigm of rewilding has taken hold. Rather than push forward an agenda of ensuring all land work to directly produce for human needs, an understanding has emerged that we can return land to a more natural baseline and that a diverse, wild, natural ecosystem benefits humans and non-humans alike. Rejecting our historically exploitative influence, renaturation offers us a new framework to consider humanities role in the environment as fundamentally hopeful. We can repair our connection to the natural world and act as champions of its proliferation.

However, the road towards this vivacious future is riddled with myriad challenges. How do we support a natural system to rebuild itself? How do we know if our decision-making is just or impactful? To whom should we choose to focus our attention and to whom do our actions ultimately benefit? Ecological systems are webs of complex relationships, whose true nature can remain a mystery even after a lifetime of study. Today, however, we live in the age of computing and stand on the cusp of the world of artificial intelligence - what constituted a lifetime of work just a few decades ago, can now be done in an increasingly small fraction of time. With the emergence of big data and developing technologies, we now have the capacity to engage with nature at a level previously impossible; environmental monitoring has never been more affordable and data analytics can clarify patterns too abstract for a human brain to recognize unaided.

It is at this intersection of ecology and big data that this thesis stands. The problem tackled here is how to leverage geospatial and Internet of Things (IoT) technologies and tailor them to help engage more deeply with the world around us and improve its condition. Specifically, this masters project looks to apply the IoT in the context of environmental monitoring for the renaturation of the Kalterbach - a stream just north of Munich in the South of Germany. This thesis explores the practical capacity for big data to help drive ecological decision using a wireless geosensor network which can continuously and remotely collect information on various aspects of the condition of the stream, specifically water temperature and water level; the goal is to develop and install an open-nature sensor network, characterize the current and future challenges associated with implementing this IoT technology, and demonstrate utility of such data in the context of renaturation efforts. The network and its data hope to clarify the trade-offs between the creation of various habitats at the Kalterbach and ultimately improve the natural quality of the stream.

As with all ecologically relevant projects, the renaturation of the Kalterbach requires diverse, interdisciplinary thinking to improve upon the current condition. Land connects a broad web of human and more-than-human actors and, as such, the system supporting decisions with land use or land change must somehow accommodate this complexity. Emerging geospatial technologies - when correctly implemented within the decision making process - could help collect and organize ecological knowledge such that it benefits and mediates between land's many stakeholders. This thesis aims to apply IoT for support in ecological decision making and establish a sensor network which provides relevant data in an easily accessible format over a period which extends throughout the lifetime of the project.

1.2 Central Concepts and Terms

Internet of Things:

IoT is a revolutionary technology that connects everyday objects and devices to the internet, allowing them to collect and exchange data. This interconnected network of smart devices enables automation, remote monitoring, and data-driven decision-making across various industries, from smart homes and cities to healthcare and manufacturing.

Geosensor Networks:

Geosensor networks (GSN) are interconnected systems of spatially distributed sensors that collect real-time data from the physical environment. These networks enable the monitoring and analysis of various geospatial phenomena, such as weather conditions, air quality, traffic flow, and environmental changes. Geosensor networks play a crucial role in fields like environmental monitoring, urban planning, disaster management, and precision agriculture, providing valuable insights for decision-makers and researchers to better understand and respond to dynamic spatial patterns and events.

Renaturation:

Renaturation - potentially also referenced as rewilding or environmental restoration - refers to the process of restoring or revitalizing natural ecosystems and landscapes that have been degraded or altered by human activities. This ecological restoration effort aims to reverse environmental damage by reintroducing native plant and animal species, improving soil quality, and re-establishing natural water flow patterns. Renaturation projects help promote biodiversity, enhance ecosystem resilience, and mitigate the negative effects of urbanization and industrialization.

Land Governance:

Land governance encompasses the rules, policies, and practices governing land ownership, use, and management within a specific geographical region or jurisdiction. Effective land governance is essential for ensuring equitable access to land resources, protecting property rights, and promoting sustainable land use. It involves legal frameworks, land tenure systems, land registration, and land-use planning, with the overarching goal of promoting social justice, economic development, and environmental sustainability.

1.3 Research Objectives

The guiding objective of this thesis is as follows:

> To implement a GSN in an open nature setting at the Kalterbach and to assess its success, the utility of its data for informed environmental decision making, and the potential barriers to future uptake of this technology in similar use cases.

This primary aim can be deconstructed into a series of secondary and research specific objectives. These objectives represent smaller steps on the way to the larger goal stated above. These would be to:

- Understand the requirements of a GSN and how to move the technology from theory into practice
- Install appropriate hardware in the Kalterbach such that accurate and relevant data can be received and stored for later analysis.
- Analyze and present the data in a way that provides useful insights otherwise unattainable for decision making in the renaturation of the stream
- Use this GSN as an opportunity to learn and characterize the success, challenges, and opportunities to broader utility of IoT technologies in the context of environmental monitoring.
- Ensure the network has the capacity to continue operating long after the completion of this thesis by communicating lessons learned and means of upkeep to the relevant stakeholders
- Recommend future directions for this technology and ways of improving upon future projects.

1.4 Research Questions

Structuring these research objectives are several research questions. The broadest inquiry is as follows:

> Explored in the context of habitat creation for vulnerable species at the Kalterbach, Munich, Germany, how can IoT and GSNs be implemented for decision support in natural resource management and ecological renaturation?

Additional questions moving forward this research include:

- Logistically, how can a project like this be run to completion and what administrative structures need to be built in order to ensure success?
- What are the technical limitations of this system and at what point should a challenge be seen as simply a technical impossibility rather than a lack of financial, knowledge-based, human, or time resources?
- What type of data, at what resolution, and after what level of processing is needed for this project to be useful to and inform the renaturation of the Kalterbach?
- How should we measure the successes and failures of this project and in what ways can we organize this learning to guide future application of this technology?

1.5 Motivation

This research is motivated primarily by the desire to actualize the theoretical potential of IoT and help natural systems to reap the benefits of big data. IoT and GSNs have garnered much attention in the past few years and while its hype has begun to move into real world significance, questions remain on the technologies applied utility. In more controlled settings, IoT has already proven its worth; with a good connection between the receiver and the transmitter as well as a regulated external environment which does not threaten the sensor hardware, IoT can bring a lot of good. Curious about monitoring your indoor air quality to improve health? If you have an internet connection this can easily be accomplished. Measuring ambient humidity in a greenhouse for food production? Set up a Bluetooth receiver and you are good to go. Counting the number of people visiting an urban center to minimize crowding? Cities are a hub of human activity and connectivity, finding a gateway should not be an issue.

However, things become much more volatile and complex as we move out from a controlled setting and further from anthropocentric space. Sensors are open to the elements and the challenge lies in connecting these remote locations for an extended period so they can be understood and therefore properly cared for. The more we know about how our actions impact ecologies outside our own, the more we can modify our actions and mitigate our harm.

In addition to wanting to epistemically build a stronger understanding of how IoT can be implemented in natural settings generally, this thesis is motivated additionally by the concrete intention to help the renaturation of the Kalterbach. This renaturation has been passionately pushed forward by the community and its successful completion increases biodiversity and help to build a more resilient ecological system. The data from this GSN can resolve disputes between various stakeholders and provide an empirical direction forward for the stream.

1.6 Significance

A successful installation of a GSN at the Kalterbach has layered significance whose exact importance depends on individual stakeholder perspectives. Naturally this project has immediate, personal importance to the Verein Dachauer Moos (VDM) - an NGO responsible for the renaturation - and the communities and people who live around the Kalterbach. Improving this system improves their lives - it means more fish to catch, more flora and fauna to commune with, more rich an experience of the world and all those who inhabit it. Additionally, this project has significance to the many non-human actors whose habitat is expanded and who are given more space for life at the stream.

Beyond this more personal meaning however, there exists a clear epistemic and academic significance to this work. Although the field of IoT is fairly mature, IoT for open-nature environmental monitoring remains an emerging one; especially in the use case of ecological renaturation, the nascence of this technology means many unknown must be worked through. While several studies have recently been published dealing with its practical application, few of these investigate open-nature scenarios [39, 40, 49]. The few IoT projects that do take place in remote, natural settings are often highly funded and undertaken by governments or international institutions [3, 37]. This network at the Kalterbach is unique in that it not only explores the feasibility of open-nature GSNs for collecting environmental data, it also aims to provide this at a budget affordable for NGOs and even the general public. By understanding if this technology is applicable for such use cases and how it can be improved to allow for future uptake, we set ourselves down a path which could influence power structures of land governance and human-environment interactions. Often it is individuals and small communities who are most impacted by the exploitative, polluting practices of larger corporations or governments - by giving them power to collect data and document empirically, at scale, the negative influence of more powerful actors, agency is shifted towards those directly interfacing with the land and specific ecologies.

1.7 Outline

The thesis is structured as followed:

In the **first** (and current) **chapter** a brief overview of the research is provided. Basic concepts, central to an understanding of the broader text, are explicitly defined. The motivation and significance of the work are outlined.

In **chapter two**, a background of the Kalterbach, its history, and the relevant conflicts surrounding it's renaturation which precipitated this thesis are given. This background is followed by a review of the literature specifically focused on IoT as it relates to environmental monitoring and the theoretical significance of IoT to improve land governance.

Chapter three begins with the practical component of the thesis and outlines the methodology used to address the research questions put forward in the introduction.

Results are presented in **chapter four.** These results reflect the interdisciplinary nature of the thesis with consideration given to stakeholder mapping, data analysis and visualization, as well as project assessment in that order.

Building from these results, **chapter five** reflects on the learning and contextualizes the work more broadly. It considers the strengths and weaknesses of the thesis, how this learning can be moved forward for future IoT application, and the connection between the technology and governance.

The thesis is concluded in **chapter six** with an overall summary with one eye focused on the holistic relevance of the work.

2 Background and Literature

2.1 The Kalterbach

Just north of the city of Munich in the quaint Bavarian countryside, lies the Dachauer Moos - a former wetland with a rich history and a plethora of unique flora and fauna who call this place home. Crossing through this now drained swamp, a complex series of canals, rivers and streams have been constructed to direct the flow of water and render the land capable of agricultural use. It is one of these canals, the Kalterbach, who plays the main character in this thesis and whose story we will concentrate on here.

2.1.1 History

Starting at the clear, blue Feldmochingersee in the south, the Kalterbach runs over ten and a half kilometers across farmland, forest, and meadows before depositing into the Amper River at its northernmost end. The cold clear waters of the Kalterbach are home to many species of plants, fish, insects, birds and some mammals, including beavers who have recently been reintroduced to the region, and of course humans, who live, work, and play along its banks.

The Kalterbach and its source lake the Feldmochingersee are primarily fed through groundwater as a result of the unique geological structure of the region. The original swamp - the *Dachauer Moos* which predated the Kalterbach - was formed as a result of glacial flows which pushed northward down from the alps, during the last ice age. As the glaciers flowed down from the alps they brought rocky sediment with them and scrapped soil on the land surface. These behemoths formed the environment in unique ways and are responsible for the long, flat, north-sloping gravel plans characteristic of the landscape surrounding Munich as well as the hilly topography just north of the city (*Tertiärhügelland* in German) which delineates the historical, northernmost reach of these glaciers. Today, glacier- and snowmelt seeps down from the alps and flows through the earth northward, eventually accumulating at the low elevation in the *Dachuer Moos* just before the higher elevation of the *Tertiärhügelland* [24].

In the ancient past, all along the northern extent of the gravel plans, swamps and wetlands stretched along this border. While evidence of them can still be gleaned today[1], much of the area where one would geologically expect to see these wetlands are today productive farmlands. What allowed for this change? Starting at the beginning of the 20th century, with skyrocketing populations and urban migration, pressures on land increased. Land became an entity to control and mechanize. As such, starting in WWI, but continuing through to WWII, the swamps were drained through the construction of deep canals by French prisoners of war and later those interned at Dachau concentration camp. These canals funneled groundwater and directed water quickly to outlet into the Amper.

While the resulting land was hyper productive given the rich soil which accumulates in highly dynamic wetlands ecosystems, the environmental impacts were tragic. Not only did it obliterate a largely untouched, biodiverse ecosystem (*Urland*) from which large amounts of carbon had

[1] Take for example, the neighborhood of Moosach in Munich, whose name comes from the German Moos - translated directly into English meaning "moss" and which carries the same meaning in everyday spoken German. Previously, Moos was used as a place name for swampy areas where one might meet this type of flora. The heavy fog which sits over the neighborhood often throughout the winter months is evidence of the groundwater which accumulates beneath it.

Figure 2.1: *The Kalterbach flows just over 11 km northward from its source at the Feldmochingersee on the northern most border of the city of Munich, Bavaria towards the Amper river Source: Author, Copernicus Land Monitoring Service*

been sequestered, many of these changes remain permanent [24]. Today, nearly a third of the former wetlands are sealed by building and settlement development. However, motivated by the realization of a chaotically warming planet (and maybe, more hopefully, by an inherent goodwill to improve the lives of the living creatures who share with us in this home), opinions on the environment and function of land have changed. Recently, there has been a strong push by local, state, national, and international bodies to help rewild the ecologically one-dimensional European landscape and improve the environment for a host of human and non-human actors.

2.1.2 Renaturation

Take a moment and imagine a stream. What comes to mind? A blue, winding ribbon meandering its way through a landscape, deciding on one direction before changing its mind - once, maybe twice - and bending back to some other far-off destination, its end goal not immediately clear. The banks are full, overflowing, and green with reeds, grasses, shrubs. Fallen trees lay to rest across the current, the flowing water forced to find another path around. Perhaps in some stretches the water spools out into deep pools, taking a short rest before continuing along, sometimes speedily, over boulders and rapids.

As a product of men, the Kalterbach has few of these features we might consider inherent to a natural ecosystem. The Kalterbach often runs straight as an arrow towards whatever destination it feels so forced to achieve; all flora expected at a river bank - the lush habitat for so many forest creatures - have been replaced with rows of trees, marching orderly right along with the stream. In its one hundred years of haste, the stream has actually sunken into the landscape, eroding steep slopes down to the water as the current swiftly pulls sediment along. The water has no bends to bump into, to slow down on, and consequently this affects water quality and limits complex ecological niches for diverse life to thrive. More a machine than an opportunity for life, the Kalterbach now remains relatively void of biodiversity and ecological functionality, however, considering humanity enabled such a situation, we are now presented with an opportunity to improve our former mistakes. Today the situation is beginning to change for the better thanks to the support of a committed community of actors.

Born from a growing environmental consciousness begun in the 1960's and 70's, the Verein Dachauer Moos[2] (VDM) was established in 1995 tasked with " promoting and developing habitat and species diversity as well as climate protection in the Dachauer Moos landscape"[63]. This association engages seven municipalities - including the Bavarian capital of Munich and the city of Dachau - who are administratively responsible for the area and who have been working towards governing the land in a more ecologically minded way. VDM has undertaken several projects in service of their central goals including educational engagement with the public, flower patches (*Blühmenfäche*) intended to help support insect populations (which notably have been silently collapsing across Germany, [29]), the organization of connected habitats in Bayern, and, relevant here, the renaturation of the Kalterbach.

(a) *Original*

(b) *Recently renatured*

(c) *Fully mature renaturation*

Figure 2.2: *Comparison of sites on the Kalterbach at various stages of renaturation*

The renaturation has had several iterations. The earliest were undertaken in 1999 and were largely initiated by community members, motivated by a passion for the region and armed with a tractor and shovels. These early successes later spurred additional action and the first official renaturation was taken on by the VDM and the Water Management Office or the Wasserwirtschaftsamt (WWA) in 2005. The renaturation areas can be found in the northern part of the stream near the farm of Obergrashof. Today, this renaturation has largely matured into a rich habitat for various flora and fauna. The renaturation included the extension and reshaping of the bank, introduction of a sidearm (*Seitarm*) or bend (*Scheilfe*) in the river, addition of dead wood and stumps, small islands, native grasses, herbs, and flowers. These bends help to slow down the water, increase the ambient humidity of an area, minimize erosion, and provide breeding grounds for fish or insects [24]. Additional examples of renat-

[2]https://www.verein-dachauer-moos.de/

uration at the Kalterbach include the tolerance of beavers living in the stream as well as the construction of “dragonfly windows” which began in 2012. These Libellumfenstern, as they are called in German, are sunny clearings along the river bank where grasses are allowed to grow, providing hunting and breeding grounds for various insects, but specifically the endangered dragonfly (*Coenagrion Mercuriale*) or Helm-Azurjungfern in the native German.

It is this tiny, electric-blue insect which brings us to the current state of renaturation at the Kalterbach and which is, in large part, responsible for the genesis of this thesis. The Helm-Azurjungfern is a charismatic little dragonfly who lives around streams and brooks across South-Western and Central Europe, particularly finding home in the flat, swampy areas around the Alps (*Alpenvorland*). They live their entire larval development in the water and prefer sunny stretches of aquatic grasses in slow moving waters, ideal for hunting, breeding, and living [54]. Unfortunately however, they are currently listed as "critically endangered" under Germany’s “Red List” due to dwindling habitats and, as such, are protected under the European Habitat Directive (*Fauna-Flora-Habitat Richtlinie or FFH Richtlinie* in German) [19]. The Habitat Directive of the EU was established in 1992 and provides a legal framework to encourage member states to protect and promote vulnerable habitat. This legislation led to the development of the Natura 2000 protected areas which covers 18 percent of Europe’s land surface and 8 percent of its marine areas, making it the largest network of protected habitat in the world. Many projects have sprung from this original landmark legislation and the renewed interest in the Kalterbach is one such example.

Figure 2.3: *The Helm Azurjungfern ; source: Hans Schwaiger, Verein Dachauer Moos*

In the past decades, the Kalterbach has only ever been renaturalized in certain areas; now however, an upgrade along the entire length of the waterway is being undertaken. The "Model Project for the Renaturalization of the Kalterbach" (*Modellprojekt zur Renaturierung des Kalterbaches*) will run from 12/2023 to 12/2026 and aims to systematically improve the streams nature conservation and hydromorphology. In addition to falling under the management laid out for the Natura 2000 site "Remnants of fen and ditches in the Dachauer Moos” (*Niedermoorreste und Gräben im Dachauer Moos*) as part of the European Habitat Directive, the project at the Kalterbach is also legislatively conceived under the European Water Framework Directive (WFD) [48]. The WFD represents a landmark in European environmental governance and is the main law regulating water protection for member states; the WWA of Munich uses this legislation as the basis for its watercourse conversion concepts (*Gewässerentwicklungskonzepte*) not only at the Kalterbach but for all its other water body renaturation projects [45]. Finances for the renaturation are directed from the Bavarian Nature Conservation Fund, the municipal district of Upper Bavaria, and with additional proceeds from the Glücksspirale, a state lottery. The Dachauer Moos e.V. association conceived the project and also assumed responsibility for it. The project management as well as the planning work was assigned to the office Terrabiota[3]. Project partners are the government of Upper Bavaria, the WWA Munich as well as the municipalities bordering the Kalterbach, the lower nature conservation authorities of the districts of Dachau and Munich and the state capital Munich. Other stakeholders will be involved in the project via a working group accompanying the project.

In the run-up to this official renaturalization of the Kalterbach, the VDM has already extensively renaturalized a section of watercourse over a length of about 300m in 2021 with two stream diversions, islands, pools, shallow bank and shallow water zones. While these changes all bring us closer to reconstructing some semblance of the diverse habitat long-destroyed, ecological systems are complex and never so simple as we humans would like to believe them to be.

[3]https://www.terrabiota.de/

Renaturation remains relatively nascent and much has to be learned how (or even if) these changes ultimately impact the Kalterbach for good. No decision is without consequence and building a habitat ideal for one species often necessitates the destruction of habitat for another. It is the job of landscape planning to mediate these conflicting interests [31].

A dispute central to the Kalterbach at this moment concentrates again on the Helm-Azurjungfern and specifically their relationship to the many fish species who share in their home. While habitat for the dragonfly involves thinning trees from the banks of the river to encourage warmer ambient temperatures and the growth of aquatic grasses, the open canopy resulting from these dragonfly windows increases solar radiation on the brook and has the potential to drive up the water temperatures. Higher temperatures decreases oxygen saturation necessary for healthy fish populations threatening species of particularly concern such as Thymallus thymallus (Greyling or *Äsche* in English and German respectively) and Alburnoides bipunctatus (or *Schneider* colloquially) [63].

Successful ecological rewilding navigates these trade-offs in such a way by finding balance in the system and maximizing biodiversity while minimizing human dominance and control. Renaturation should reestablish trophic interactions and ecological processes, in order to encourage a self-sustaining system which may not necessarily match absolutely the human desired outcome or work exclusively to human benefit [14]. Finding that balance requires careful observation of the ecosystems we attempt to rewild and a deep understanding of the landscape we claim to be supporting. As we meddle at the Kalterbach, we must be truly aware how our actions impact life in this body of water - good intentions are not enough to encourage good results. We cannot force the human desire to see more of the Helm-Azurjungfern at the cost of suffocating the fish who also live there. A good renaturation of the Kaltebrach embraces adaptability and inclusivity and establishes a resilient, self-sufficient, biodiverse ecosystem. We can only reach these goals however if we have an accurate picture of our influence and impact of our actions.

2.2 The Internet of Things and Geosensor Networks

A technology which may help improve our ability to monitor the situation at the Kalterbach and one which, in general, has the potential to positively impact many aspects of modern society is IoT. Simply imagined, IoT aims to connect physical objects and places via the internet through the installations of many real-time sensors within our environment; by tying these physical entities together using radio frequencies, one can clarify complex relationships and optimize their utility [10]. Rapid developments in communications technologies have made the emergence of an IoT possible. The miniaturization of computer chips particularly in the context of radio frequency identification (RFID) have played major roles in enabling the tracking and connection of the physical world within the virtual one [60]. The possible entities one could connect and the resulting applications of such a technology seem limited only by imagination; in precision agriculture, farmers can identify the exact water requirement for a crop, in healthcare, a doctor might use a skin patch connected to the IoT to monitor a patient's health, in city governance, planners could identify times and areas of high traffic or mitigate against unsafe air pollution [57]. The revolution charted by such a powerful technology is as tantalizing as it is provoking.

2.2.1 Hardware and Architecture

Established conceptually at the turn of the century, IoT garnered intensive theoretical attention in the early to mid-2010s and now, in the last decade, has more rapidly begun to move from hype to practice [10, 34, 59]. With just under 8 billion devices connected to IoT in 2019, that number is expected to be over 25 billion by 2030 - a marked change which brings with it a revolution in how we understand our world [6]. In its most basic form, the IoT follows a three stack architecture divided into the application, network, and perception layer. The perception layer includes the sensors and hardware which collects data at the site and interacts with the physical world, the network layer connects the devices to other sensor things and servers, and the application layer delivers the data to the user. In some cases, the architecture can be expanded to include three additional layers which include the transport, processing, and business layers [57].

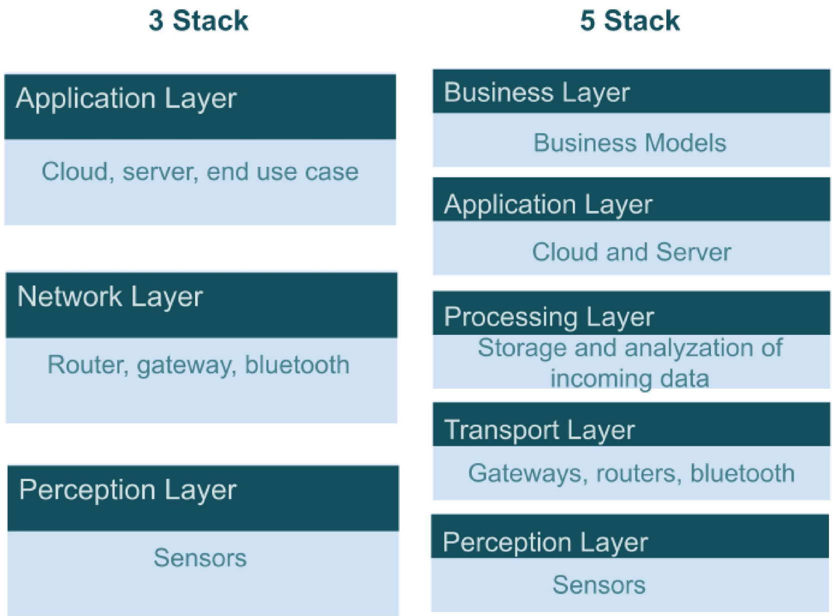

Figure 2.4: *Overview of the IoT architectures; source: modified from Sethi, 2017*

Focusing on the perception layer - the actual sensors on the ground - theoretically, any quality of the physical environment could be measured and recorded. Today, a wide range of sensor have been fashioned for us in the IoT: Medical sensors can measure daily functioning of the human body including things like heart pulse, body temperature, respiration, blood pressure; many sensors exist in our phones such as GPS, magnetometers which can act as a digital compass, even our microphones and camera fall under this category; of course in the environmental monitoring domain, things like air quality monitoring, temperature, or barometer all apply to capacities of the perception layer. These sensor probes are connected to a node which is the physical device and the "Thing" in IoT. The probe records its data through this node which is responsible for housing additional hardware vital for sending this data through and uploading it to a cloud [57].

With this data collected from the physical environment, the next question is how to move that data to the user. Within the transport layer - a sublayer of the network layer - many different methods can be used to transmit data from its source. Transmission occurs over WiFi, Zigbee, Bluetooth, Z-Wave, LoWaRAN, and LWPANs to name but a few. Each of these transmission methods offer various benefits and shortcomings and are more or less fitting to various applications. Some transmissions such as Zigbee or Bluetooth are more fitting for short distance data transmission. Conversely, the LoWaRAN (Long Range Wide Area Network) transmission allows for data to be moved across far distances with very little power consumed. The table below outlines popular transmission methods available and the advantages to each [6, 32]:

Table 2.1: *Common transmission types for IoT, their spectrum information, and a short description of their qualities, benefits, and shortcomings*

Transmission Type	**Spectrum**	**Description**
Wi-Fi	2.4 GHz or 5 GHz	Allows for high data volumes to be sent through the internet via a Wi-Fi router. This option is technically accessible, mobile, and broadly applicable if the connection is possible.
Bluetooth	2.4 GHz	Short-range, wireless communication network often used for wearable and home devices. Can have interference problems and relatively higher power consumption compared to alternatives such as Zigbee.
Zigbee	2.4 GHz	Designed for short-range and low data rate applications, Zigbee has advantages in its lower power consumption and simple protocol stack. This makes it a suitable candidate for smart home applications.
LoRaWAN	902.3 - 914.9 MHz	Relies on unlicensed radio spectrum, allowing for data transmission without fees and without reliance on cellular networks. LoRaWAN has far area coverage and consumes low amounts of power, making it suitable for remote monitoring tasks. A disadvantage is that it cannot handle high bandwidths and it relies on the installation of gateways in the physical environment, which can be costly.
Cellular Networks	Varies by technology (e.g., 3G, 4G, 5G)	Suitable for long-range and remote monitoring, cellular networks offer an advantage over LoRaWAN in that they offer higher bandwidth data transmission and global connectivity. This said, there is often an associated subscription cost to access the network infrastructure.
Satellite	Varies by service	While satellites offer constant, global coverage without infrastructure limitations, the overhead and access costs can be high and may require more power consumption.

While one sensor transmitting information across one of these transmission methods does in-and-of itself provide valuable insight to the world around us, the exciting implications of this technology present themselves if we consider a whole constellation of sensors working to investigate the environment together. GeoSensor Networks (GSNs) are a powerful method of physically connecting “things” into the IoT. A GSN consists of many sensor “nodes” which are each equipped with a powersource, a transceiver, a computing unit, and a sensor interface which collects data on the unit of interest [46, 65]. The transceivers send the remotely sensed data over a gateway using radio frequency which then allows the data to be accessed by the user through the internet. These networks can be established in a range of physical locations which influence the necessary hardware and transition schemes.

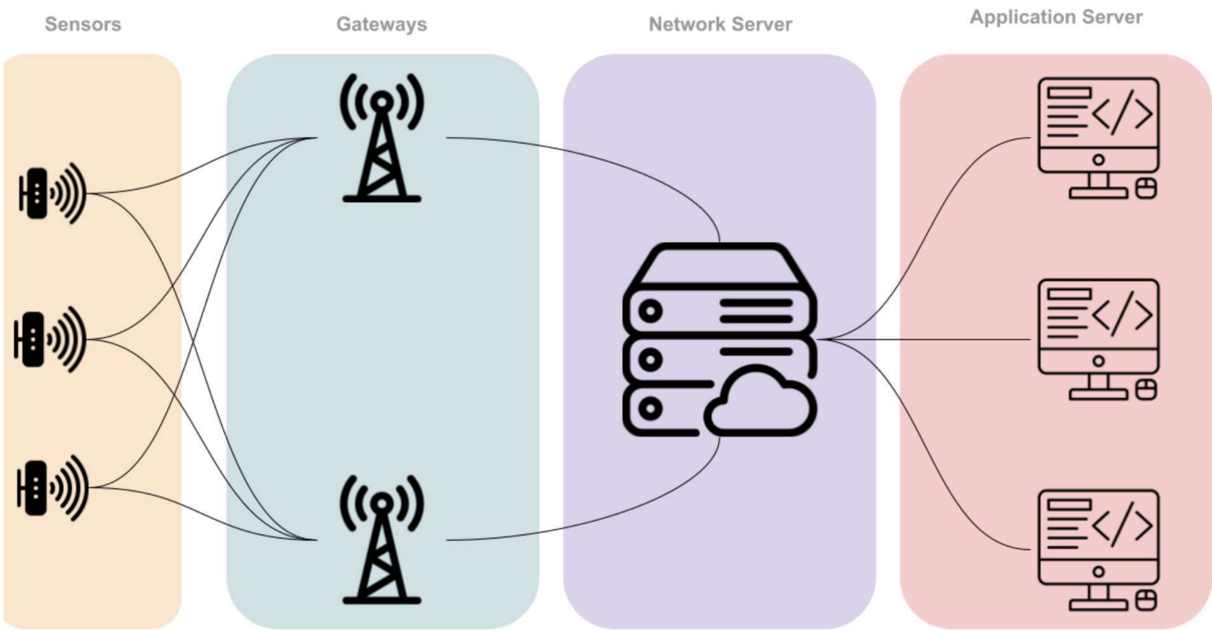

Figure 2.5: *Diagram illustrating the basic path of data under the LoWaRAN Transmission from multiple sensor devices through on to its end use*

2.2.2 LoWaRAN

In recent years, the LoWaRAN transmission has become increasingly popular in GSNs for its low power consumption method, the open accessibility of gateway connections, and its ability to transmit over far distances [32, 55]. For outdoor applications and remote environmental monitoring schemes, these capacities are particularly relevant and therefore is a popular choice for such use cases. Let's look at how GSNs collect and send data under this LoWaRAN transmission as a way of understanding the broader functionality of such systems.

Figure 2.5 outlines the transmission of the data under LoWaRAN. On the far left of this figure, we see a sensor network, assumedly collecting data in the field. Individual sensors in this network then send their data over a specific radio frequency to gateways which have been established in various locations in the landscape and act as way-stations for the incoming data. A data packet from a sensor can be receive by multiple gateways, however only the sensor-gateway connection with the strongest signal will be used to transfer the packet to the network server. Signal strength is mediated mostly by proximity, however obstacles in the landscape also play a role and can cause a weak signal connection. From here, the gateways direct the observations through to the "network server." Before the physical network has been established in the field, the individual sensors must be established as cloud entities within the network server. This is accomplished using a set of unique codes which are associated with their hardware and identify each device. Once a sensor has been created as an entity in the network server, the gateway can connect the incoming sensor data to a location in the cloud.

Importantly however, the network server does not store any data. The storage of sensor data happens on the "applications server." The application server and the network server are independently operating systems which run according to a set of data standards (see Section 2.2.3). Data is transmitted across the network server and the application serve through a series of payload conversations under Message Queuing Telemetry Transport (MQTT), to name one specific example. This messaging protocol allows for effective communication between devices, servers, edge computing systems, and cloud-based applications. Data can be then be accessed from the application server by users through a variety of platforms.

LoWaRAN is an open standard and protocol. This means the infrastructure is accessible to anyone looking to join the network and helps to proliferate the technology by bringing down costs; if you buy a gateway for your devices, other sensors in the area could route through this gateway to the network server. A popular community-driven LoRaWAN network is "The Things Network" [4] (TTN). TTN is an open network which operates as a global community of volunteers and contributors who set up and maintain LoRaWAN gateways. These gateways act as access points for LoRaWAN devices, similar to Wi-Fi access points. TTN provides a mapping of its gateways and their global coverage [5] which helps to identify the viability of a planned GSN before it is installed. If there appears to be poor connection in an area, a gateway[6] can be bought ahead of time for a relatively low cost of 600 €, thereby expanding the network. An example of this mapping for the city of Munich can be seen in 2.6.

The open accessibility of this network may raise concerns regarding data security. While private LoRaWAN networks are available, it's important to note that LoRaWAN inherently supports end-to-end encryption. This ensures that data transmitted from a device to the network server and vice versa remains confidential. The encryption is achieved through the use of unique keys associated with each sensor device. These keys are represented to the user as long series of alphanumeric characters and are linked to a specific modulation on the transmission frequency. These modulations are used to encrypt and decrypt payloads and are only accessible to users with access to the corresponding sensor key.

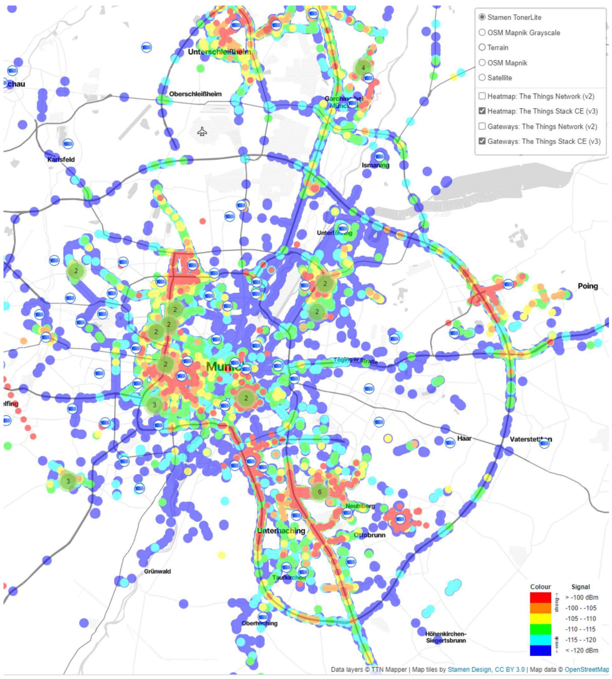

Figure 2.6: *Heatmap for Munich showing connectivity to TTN gateways; source: TTN Heatmapper*

A unique feature of LoRaWAN is its modulation scheme, called Chirp Spread Spectrum (CSS),

[4]https://www.thethingsnetwork.org/
[5]https://ttnmapper.org/heatmap/
[6]https://connectedthings.store/gb/lorawan-gateways/outdoor-lorawan-gateways/the-things-outdoor-gateway-868-mhz.html

which allows for long-range communication with minimal power consumption. This modulation technique spreads the signal over a wide frequency range, making it robust against interference and capable of penetrating obstacles and reaching distances of several kilometers, ideal for remote or rural areas. LoRaWAN defines several data transmission formats with different payload sizes to accommodate various use cases. These formats are known as "data rates" and are identified by their spreading factors (SF) [43]. Lower spreading factors (i.e. SF7) offer higher data rates but have shorter range and high power demands, while higher spreading factors (i.e. SF12, the highest) provide longer range at the cost of lower data rates and decreased power demands. The maximum payload size for LoRaWAN is typically 51 bytes. LoRaWAN supports adaptive data rate (ADR), which allows devices to adjust their data rates dynamically based on the network conditions. This ensures optimal performance while conserving battery life for IoT devices - an extremely important feature when establishing a GSN in a remote area with only a battery as a power source.

2.2.3 Data Standards and Best Practices

While several domains pose significant challenges to the uptake of the IoT - these include coverage issues, security and privacy, and energy efficiency - interoperability between devices, data, and data platforms has consistently been identified as one of the most limiting factors to date [34, 47]. Due to an increase in heterogeneity of data and sensor types, it is estimated that IoT has seen substantial setbacks in broader uptake of the technology; however, in response to this, various standards and practices have been established in the installation of GSNs and the storage or utilization of their data. Any network must be aware of its broader operability and be established with this goal in mind from the beginning.

The Open Geospatial Consortium (OGC) is an international voluntary consensus standards organization which can be used in the development of the IoT network at the Kalterbach [33]. Specifically, the OGC SensorThings API which was developed as a means of organizing IoT data and optimizing its interoperability both to the user and across platforms and projects, should be followed for most impactful results [42]. This API has successfully improved IoT network development by facilitating queries and managing the large amounts of data associated with IoT technologies with much more ease; the SensorThings API also makes use of the RESTful API which allows for easy access of sensor data using HTTP. Other ways that the API has changed the IoT space is by encouraging semantic interoperability and the incorporation of other methodology for discovering sensor data. Since being introduced in 2016, SensorThings API has helped to standardize the industry and now most preassembled IoT devices and IoT infrastructure are pre-fitted to match these standards.

The SensorThings API is encoded in JSON format and follows a simple architecture which maps together five main entities - Observations, Observed Properties, Datastreams, Sensors, and Things - and includes two additional classes - Location and Feature of Interest. Individual, physical ‘Sensors’ are mapped into this API (e.x. LoWARAN Temperature Sensor Model 13) according to unique identifiers associated with each device and an ‘Observed Property’ based on the physical hardware of the device is defined (e.x. Temperature in Celsius). Then the parameters for each ‘Observation’ can be input and is an individual data point associated with a point in time which repeats with a specified frequency. These three qualities are combined to create a unique ‘Datastream’ which acts as a central node directing the information recorded at the sensor to the Things entity which refers to the actual ‘Thing’ in either the physical world or the information one which you are measuring - for a topic such as river monitoring, this could be the water temperature at a specific place and time.

Several implementations of this API exist in an open source format including: Whiskers, GOST, FROST, SensorThings HcDT Charting SDK, Mozilla STA, or 52°North STA. Especially important

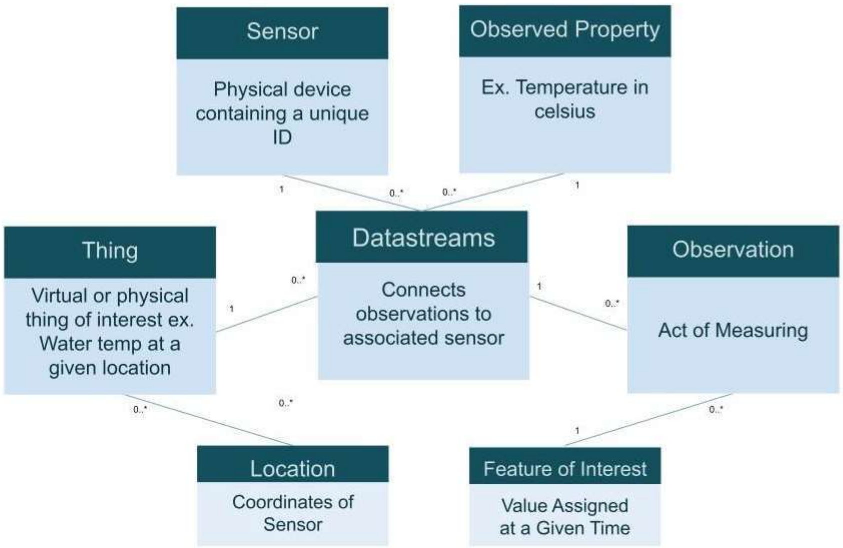

Figure 2.7: *Simplification of the UML diagram underlying the SensorThingsAPI data model*

in the German and European context, but with additional global relevance, the Fraunhofer Open Source SensorThings API Server (FROST-server)[7] has been implemented by the Fraunhofer Institute[8] - a global recognized applied research organization - and has become a popular choice for GSN applications and IoT in general.

2.2.4 Data Mining and Processing

Table 2.2: *Standard functionalities for data mining with IoT data*

Functionality	Description
Classification	Takes a data series and assigns it into already known classes based on various characteristics
Clustering Analysis	Divides data into meaningful groups by matching data patterns to their most similar categories
Association Analysis	Analysis aims to make associations between two items or data sets, by extracting rules which dictate the relationship between them and the ways they change or frequently occur together
Time Series Analysis	For data which varies with time, this analysis looks to clarify the dependency of the data over those time intervals
Outlier Analysis	A type of time series analysis, the primary objective of this data mining is to discover irregularities over a period

The vision of IoT ubiquity is a future full of promise, however, in such a world, another challenge quickly presents itself - what to do with all that data? IoT produces massive amounts of information about our planet and the happenings taking place here. Managing, organizing, processing, and visualizing that data for various uses becomes an extremely important task for

[7] https://github.com/FraunhoferIOSB/FROST-Server
[8] https://www.fraunhofer.de/en/about-fraunhofer.html

those establishing GSN. Without this data handling step, the valuable insight collected by an IoT system does not precipitate societal benefit.

While the data collected from IoT sensor networks is robust and rich with information, the sheer amount can be overwhelming. Data mining is the process of clarifying trends and patterns from large amounts of information by applying algorithms to extract this information - the size of these datasets often means that the most interesting relationships are unable to be seen by the human brain alone, therefore computing technologies, and increasingly artificial intelligence, have to be utilized[15]. Under the umbrella of data mining, there are several functionalities which elucidate specific patterns. A brief summary of these functionalities has been prepared here from Chen 2015 in table 2.2 above.

2.2.5 Visualization and End User Application

Time series analysis and outlier analysis are among one of the most important data mining approaches for IoT, especially in the context of environmental monitoring. Trend analysis is often computationally inexpensive, but still provides a valuable insight into the realities on the ground - once these trends are detected, the origins of the changes can be theorized and cue decision makers and researchers into the processes behind the data. Various methods exist to clarify the trends in these long time series data sets including statistical modifications such as the Mann-Kenndel test, moving average smoothing, or the Fourier transformation [23]. Additionally, beyond regular or continuous trends, understanding unexpected values helps to paint a broader picture of the data and therefore the environment. Anomalies in a time series data set can be divided into point, contextual, and collective anomalies [58]. Point and contextual anomalies occur for a short time, but do not contribute to the overall trend of the data (ex. a sudden decrease in water temperature due to run off from a nearby farm), while a collective anomaly is the process in which the entire dataset is affected (ex. Rising temperatures due to consistent heating by the sun). Used in tandem, both these trend analysis and anomaly detection can additionally be used to smooth IoT data - an important step in making data interoperable and usable. Within the SensorThings API, this process is not supported however, instead this time series analysis should be externalized and can be done with any standard programming language such as Python, R, or Java.

Finally, once the relevant data has been collected and processed, it must be communicated to relevant stakeholders. The method of data visualization will depend on the intended audience; to a panel of scientists, more complex and mathematically intensive data visualization can be applied, however for the broader public, and interactive, simple, and engaging visualization would be preferred. With such a volume of data, IoT time series can be manipulated in a dizzying number of ways, however, for the purposes of this thesis, the primary objective is to illustrate the utility of this technology for decision makers, not to extract every ecological pattern present at the Kalterbach. As such, when handling the data, visualizations should be made to exemplify IoTs potential and provide an entry point for future, more complex data analysis such as hydraulic modeling.

Many visualization techniques exist to organize IoT information and monitor incoming data in real time; a particularly relevant open source tool is Grafana[9] which can directly connect to IoT data streams and plot this data in creative ways [7]. This platform offers an opportunity for the data owners to monitor the functionality of the network and also can help communicate results in the form of graphs and maps. This platform offers an opportunity for the data owners to monitor the functionality of the network and also can help communicate results in the form of graphs and maps. Grafana allows for real time vigilance over the network which is ideal for those responsible for operating the project - issues in functionality can quickly be identified

[9] https://grafana.com/

and mediated if deemed necessary. Additionally, the platform allows for a user interface as you can look at when data points were sent and highlight different trends by changing the time window displaying the data. One downside of Grafana however, is that in the free version, users without a password cannot access the data and therefore it limits the application as a tool to engage the public and provide them with an overview of the river. This is unfortunate as it could provide a fun way of engaging the public, increasing support, and building community around the renaturation of the stream. This limitation however applies only to the hosted solution offered by Grafana and can be overcome by self-hosting, providing full access to the dashboard and its data. Additionally, the program has limited data manipulation capacities - to carry out more sophisticated data mining such as trend and time series analysis, data processing must be externalized. Here lies an additional advantage of the SensorThings API data structure in that observations can easily be downloaded as a CSV file directly from Grafana and analyzed across software platforms. Data mining can then be carried out using various computer languages or with geographic information systems like QGIS or ESRI products.

2.3 Geosensor Networks for Environmental Monitoring

To the droning beat of the ever intensifying climate crisis, a particularly relevant application of IoT technology has emerged to aid in environmental monitoring [40]. Used with an optimal transmission method such as LoRaWAN, satellites, or cellular networks, a GSN applies particularly well to environmental monitoring because it enables long term, wide range transfer of information with minimal physical revisits.These advantages help to overcome the traditional limitations associated with environmental monitoring including the timely acquisition of data, limited scalability, or the remoteness of areas of interest [2]. However, in the case of outdoor applications, unique challenges exist and the requirements of such a GSN differ substantially from indoor systems. Best practices for establishing such a network necessitate small, cost-effective, low error sensors which have long battery life, hardware protected from harsh conditions, and can be remotely updated and configured [41]. Following these guidelines, many companies - including Intel, Cisco, Libelium, Dragino, or Arduino - now produce ready-to-use sensors that are fitting to outdoor, open nature GSN applications.

In the last few years, several studies have applied IoT through GSN for environmental monitoring, many of these specifically concern river water monitoring and can be used as a guide for this project at the Kalterbach. Several surveys have been carried out which collect information on the theoretical and practical application of GSN in water quality management [38, 39, 40, 49]. These provide a starting point for understanding the various options, permutations, and potentials of a GSN. However, although providing a good, broad theoretical basis, the reviews highlight the lack of GSNs installed and running for real world application in the open -nature setting. Additionally, many existing studies rely on short range wireless networks to transmit data such as Zigbees or 6LoWPAN, however this can be a limitation when designing outdoor, open nature environmental monitoring systems.

Although carried out at a greater scale and with a bigger budget, the smart water quality management project at the Weija dam in Ghana offers the most recent and comparable GSN based water monitoring schema [3, 4]. This system was implemented in 2020 using pre-assembled water quality sensor nodes from Libelium[10] which collected data continuously on temperature, pH, conductivity, dissolved ions, and dissolved oxygen saturation. The system can be used as a reference in method development and additionally documents challenges related to implementation which is useful to avoid similar pitfalls. This study highlighted the difficulty associated with sabotage and damage to the devices associated with being unprotected in the

[10]https://www.libelium.com

open environment, but did not identify preventative measures taken. A particularly pertinent challenge Adu-Manu, Katsriku, Abdulai, and Engmann [3] addresses is the need for recharging batteries; the Libelium sensors they chose had the option for solar cells, which helped to provide energy for the devices. As a whole, the project proved helpful for stakeholder decision making, but notable gaps in data and time constraints impact the project results.

Other GSN water monitoring schemes are less fitted to this thesis use case, however still provide a good reference for how to approach water quality monitoring using IoT. Kadir, Syukur, Othman, and Saad [37] established a comparable water quality monitoring system in Indonesia transmitting over 4G wireless networks. This system measured a similarly large amount of parameters, but was much more permanent in its design, in this way avoiding many of the hardware issues of Adu-Manu, Katsriku, Abdulai, and Engmann [3] with, of course, additional financial and convenience cost. This system was not yet installed in the river and only provides laboratory results. Another example of a GSN which has been theoretically proven to work, but not yet installed in the field was derived by Jia [35] for wetland monitoring. This paper constructed and tested LoRa-based sensors for water and soil monitoring and demonstrates the utility of such a transmission scheme particularly for remote and long term environmental monitoring.

Beyond the specific use case of water quality monitoring, several papers have been published implementing GSN in open-nature environments more generally; outdoor systems such as these share similar challenges associated with sensors being subject to the elements and transmitting in more remote areas. A common use case is in precision agriculture. The paper by Ramson, Leon-Salas, Brecheisen, et al. [51]. 2021 tested an in-field GSN for agricultural soils using LoRaWAN and can provide important insight into establishing this type of network for environmental monitoring. The method's development remains highly relevant to the challenges associated with such environmental monitoring networks and highlights the practicality of LoRaWAN for this task; this transmission method seems to be the preferred choice. This claim is additionally substantiated in the paper by Gresl, Fazackerley, and Lawrence [27] which constructs a prototype sensor network using this transmission scheme for detecting disease in fruit crops. LoRaWAN transmission also proved useful in the paper by Ragnoli, Colaiuda, Leoni, et al. [50] which implemented a tracking system for worker safety at a construction site using prefabricated sensors from the manufacturer Dragino Technology Co[11]. Meanwhile, the paper by Vandôme, Leauthaud, Moinard, et al. [62] applies GSN technologies to irrigation monitoring under a similar LoWaRAN transmission, however a central focus of their work concerns decreasing costs in order to democratize the technology to low-income farmers. They construct their own sensors as a means of making this technology more economically feasible.

An additional field in open-nature application of GSN concerns fire monitoring. Again, while the actual measured values (usually air quality sensors measuring parameters like CO2) differ from water quality monitoring, the underlying structure of GSN provides important points of reference. Dampage, Bandaranayake, Wanasinghe, et al. [21] successfully implements a fully functioning GSN using self-made sensor networks in remote, forest settings. The paper emphasizes the importance of sensor node design and placement in challenging forest environments, aiming to minimize damage from wildlife and adverse weather conditions. Sendra, García, Lloret, et al. [56] applies a similar network using a LoWaRAN setup. The paper uses the open access Things Network to host its sensors and investigates how far gateways and sensors can be from one another while still ensuring a functioning network. Like Adu-Manu, Katsriku, Abdulai, and Engmann [3] and Ragnoli, Colaiuda, Leoni, et al. [50], this paper uses prefabricated sensors. In all of these papers, prefabricated sensors seem to confer the benefit of simplifying the technical process and offering a greater scalability.

[11] https://www.dragino.com/

2.4 IoT and Improved Land Governance

Technology has always impacted how we humans think about ourselves and our fundamental role in our landscapes; to call upon the now famous paper by Andy Clark and David Chalmers, the external world extends our minds capacity to think and therefore how it sees the world [18]. Some technologies - like the wheel, the boat, the plane, the rocket - allowed us to move across space in ways we hadn't been previously able to do; developments such as writing, painting, movable type, or the internet enabled us to feel connected to people and places and times beyond our immediate environment; and others still - think the magnifying glass, sonar, the infrared satellite, made the hidden world visible and gave insight into our scale and impact on this planet we call home. Every technological development comes with it a restructuring of our internal conception of ourselves, and as such, a restructuring of our external organization of society. It is therefore paramount to understand exactly the impact a technology has and how we can leverage it to bring about the utmost good.

2.4.1 The Smart Earth

IoT disrupts our understanding of land, of space, of happenings in the world, of patterns and relationships between things. Analyzing and reflecting on the impact of this emerging technology, we can hope to optimize it for maximal gain. Especially in the domain of land, environment, and climate, so much of our historical application of technology has exploited our resources and ravaged our home. Perhaps IoT, in conjunction with other earth observing technologies, can be used to repair our relationship to space, tune us into our impacts on land, and forge an improved form of land governance.

Several recent studies substantiate the claim that IoT helps to improve our land governance and relationship with the environment. Abid, Ceci, and Razzaq [1], L. Chen [16], Ha, Huong, and Thanh [28], and Ren, Hao, and Wu [53], all empirically investigated the role that digitization and specifically information-and-communication-technologies (of which IoT is included) play in reducing emissions or improving resource consumption. These studies show that adoption of such technologies both on an individual and national scale can increase environmentally positive outcomes such as conservation of resources. This broad digitization enhances technological innovation and can help identify problems more quickly when they arise. A large review across different domains of research confirms that these forms of digitization hasten the transition to an egalitarian, sustainable society and help us meet our global sustainability goals [64]. Specifically naming IoT in synergy with GIS, they suggest that this could bolster governance and help chart forward routes to sustainable development.

This research places high praise on the potential of digital technologies and IoT to mitigate against climate change, however, it is not enough to just know that it can do good for the world; in order to fully leverage its potential, we must also understand its mechanism of action. Previous works have identified IoT as a key component of the "Smart Earth", which is a set of technologies which monitor changes on our planet in real or near-real time. Bakker and Ritts [11], taking a comprehensive meta review of the technology, reflect on the implication of the Smart Earth in the context of the environment:

> Smart Earth enables a series of shifts: the time-space compression of data availability and decision-making (which in turn enables automated real-time regulation and new prediction capabilities); the multiplication of modalities and agencies of environmental sensing; the proliferation of new environmental governance actors; and, potentially, a much higher degree of transparency in data collection, accessibility, and integration. Taken together, these innovations create the conditions for potentially significant transformations in environmental governance.

Not only does IoT collect accurate data - and more of it- on the happenings of our world, it also epistemically expands the voices and perspectives included in environmental decisions, allowing for a more holistic and broadly successful process of governance. While previously, environmental data was largely limited to state institutions, the proliferation of accessible IoT and other big data sources allows for more knowledgeable public engagement.

2.4.2 A Voice for Nature

The perspectives which it captures go beyond just including additional human voices - non-profit actors and interest groups, knowledgeable citizens, farmers and other land based professionals, etc. - it also empowers non-human actors. An emerging concept in environmental governance is the Right of Nature, which aims to imbue ecosystems and nonhuman beings with an autonomous voice in our legal systems [20, 61]. However, the method for how we give nonhuman life legal standing has been a fraught topic, especially on the issue of representation. How can an ocean tell the jury in court that it has been abused and exploited? How can the song of a bird be translated to human language for us to hear? This issue of representation and allocation of voice has been highlighted as a central struggle to the further development of the Right of Nature, with existing law generally placing the responsibility on non-state, human actors [30]. These individuals who are expected to act on behalf of the natural world benefit from IoT technologies which provide real-time communication from the ecosystems they are tasked to protect. By translating ecological processes into human-consumable data, IoT empowers all citizens to hear injustice taken upon the environment and provide an opportunity to improve this condition.

A concrete case study of the role that IoT projects can play in improving environmental governance has been observed in the case of salmon aquaculture management from 2011 to 2017 in Macquarie Harbour, Australia [9]. This case study provides the best example and the clearest analysis in the literature to date of IoTs potential in this domain. In 2011, a new fishing cap set based on a scientific model was placed on the Macquarie Harbor in Tasmania. Simultaneously, additional, real time sensors were introduced to the harbor; these included fixed place, dissolved oxygen sensors, as well as mobile sensors placed on live fish. The resulting program allowed for more data to be recorded in one day than the entire pre-2011 monitoring program. As a result, scientists were able to preemptively identify a potential environmental collapse as a result of low dissolved-oxygen in the harbor and revise the sustainable fishing cap to improve the health of the ecosystem.

The authors of this case study explore the role of environmental data as a “translator” under the framework of Actor-Network Theory, a concept from the social sciences which aims to understand how social interactions and phenomena emerge through the interactions between human and non-human actors [12]. At its core, Actor-Network Theory challenges traditional notions of agency, where agency is not solely attributed to human actors but also extended to non-human entities, technologies, objects, institutions, and even ideas. Under this theory in the case of the Macquarie Habro, Ascui 2018 posits that:

> ..environmental Big Data has agency: it increasingly influences the behavior of other actors as an unpredictable mediator rather than passive intermediary, and thus should be considered as an important actor in its own right, within the network of relationships that together constitute and enact the governance of a particular environmental mechanism

Under this framework, the role of IoT gains heightened importance. It is with this theory in mind that we embark on implementing a wireless sensor network at the Kalterbach. In doing so, we call into existence a new player in our understanding of this environment and transfer agency to the river as a whole. We extend consideration to many more actors in our network of being and force a certain level of responsibility upon ourselves to do better than we did before.

3 Methodology

3.1 Research Approach

Given the interdisciplinary nature of this masters thesis, the methodology employed to investigate IoT and GSN utility in renaturation programs is similarly myriad. Not only is the technical capacity of the system under evaluation, but also the project's functionality as a whole is being investigated. The thesis comprises four separate, but interrelated avenues of study, all of which come together to ultimately help us assess the productivity of IoT in this application case. These study areas are broken down into stakeholder engagement, network creation, data processing and project review. Each of these subcategories in the study require unique methodological approach and encourage different types of thinking for success.

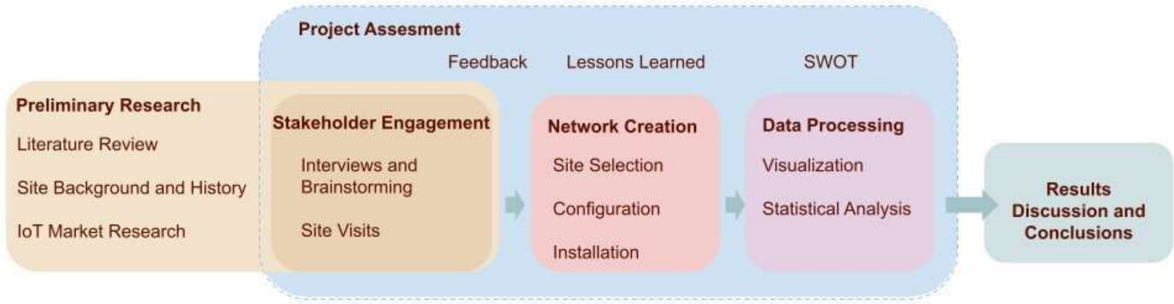

Figure 3.1: *Methodological outline*

As an extension of the preliminary research, firstly adequate **stakeholder engagement** must be carried out. As the renaturation of the Kalterbach involves many actors invested in its outcome, similarly, interest and engagements extends to installation of a GSN at the stream. In order for the project to run successfully, various opinions should be consulted, not only to secure support, but also to collect valuable advice and knowledge crucial to building the network.

With this wealth of knowledge mapped and interpreted in the connection of our own work, we can begin with the **network creation**. This section of the thesis is notably more practical in scope and focused on application. An engineering perspective as well as strong technical know-how need to be employed in order to install such a network in the real world.

Considering a network is successfully installed, the next step deals with the **data processing and visualization**. Moving from hardware to software, the incoming information from the IoT sensors must be interpreted, analyzed and made useful for the various stakeholders identified in the first methodological subsection. Various data tools and methods for effective visualization have to be identified.

Finally, behind all three of these categories is ultimately the **project assessment**. Moving the thesis work from this specific case study to a broader scale, this section should attempt to epistemically structure the learning and project this for future application. This generalization requires a systematic process for evaluation and should refer to the myriad learning throughout the work. With these overarching frameworks in mind, the following chapter outlines the specific methodology used to actualize the results.

3.2 Stakeholder Engagement

An important aspect of any good project looking to implement new and emerging technologies, is the proper understanding of how these technologies engage with existing structures of power, systems of governance, as well as their technical capacity. Especially in a thesis such as this with a clear end date and limited run time, to ensure success, consideration has to be given to the players that have been engaging with the problem at hand and who will be in charge of the technology after the masters thesis has run its course.

Before the project had begun, an introductory meeting with various stakeholders was planned to build a solid foundation off which to launch the GSN. There are several groups and individuals responsible for the renaturation of the Kalterbach, however the main administrative responsibility lies with the Verein Dachauer Moos while the technical and bureaucratic process of the renaturation is carried out by the ecological engineering and planning firm Terrabiota. Representatives from both of these firms were brought together and asked to introduce the renaturation project in their own terms followed by a discussion with representatives from the chair of Geoinformatics at the Techincal University of Munich (TUM) and I to learn all that we could about the utility of IoT at the Kalterbach. From this meeting an understanding of the actors involved in the project as well as expectations for the IoT network were collected and used as the basis for the project proposal. A list of the relevant stakeholders was generated to provide a clearer framework for the social networks involved in the project and how these networks could be used to ensure the success of the GSN. These stakeholders were then organized into a Power-Interest matrix as a means of graphically mapping the situation.

With this knowledge and the technical and practical information provided through the initial meeting, a project proposal was created and presented to the larger group of stakeholder including representatives from the Verein Dachauer Moos, Terrabiota, the TUM, WWA, and a few key community members with particularly deep knowledge on the stream ecosystem. This allowed for feedback on the initial project design and room for misunderstandings to be worked through. In this second round, additional feedback was given and incorporated into the project design which ultimately influenced the positioning of the sensors.

After agreeing on a sensor network plan, the stakeholders were regularly updated on the progress of the installation and results. This was done through email, but included several meetings to communicate the ongoing challenges and results. This provided additional opportunity for feedback in accordance with the best practices for project planning which usually prefer an iterative approach for improved outcomes [31].

3.3 Network Construction

The mapping of this network provided an essential foundation off which to move the project forward and begin developing the GSN in earnest. Through several interviews and regular consultation with the most influential stakeholders as well as the adoption of an interactive planning approach, the GSN at the Kalterbach was conceived and actualized to deliver fruitful and insightful data.

3.3.1 Sensor Selection

The initial round table discussion with the VDM, two local fishers, Terrabiota, and TUM were taken as an opportunity to understand the larger project wishes and aspirations and generate a list of requirements the GSN would ideally fulfill. This brainstorming session touched not only on longer term impacts and purpose, but also on logistical details such as finance and administration. The wish list from this original meeting included the following:

- Limited maintenance and check-ins
- Budget of 500-1000 €was deemed reasonable, with preference given to the lower estimate
- As many low-cost sensors as possible at that price point
- Temperature and water height monitoring were given the priority with other water quality indicators such as saturated oxygen content preferably desired if financially possible
- Reliable functioning in remote areas

This wishlist helped to then inform the decisions on what sensors to use in the network. A review of the literature and related works provided a good basis to understand the possibilities and optimal specifications of the devices (see Section 2.3). Looking at this literature, the importance of LoWaRAN in remote GSN becomes immediately clear; nearly all the reviewed papers (especially the most recently published research) preferred this transmission scheme for its ability to more reliably send signals with relatively fewer infrastructure needs.

With this transmission scheme decided, the next step was to choose a sensor model capable of that transmission. Firstly, one must decide whether to buy a prefabricated sensor or build their own. The majority of the papers reviewed constructed their own sensor devices, often using parts from the technologies manufacturer Arduino[1]. Various hardware components can be purchased, constructed, and configured from this supplier. When constructing your own sensor, while there seems to be potentially significant decreases in price as well as the benefit of customizable observations, a major trade off is the time and technical knowledge required to build them. The time constraints of this thesis made it unrealistic to think we could create multiple unique sensors and implement them in the water. Additionally, while most of the studies were approaching GSN from an exploratory, scientific, or theoretical perspective, this thesis is heavily concerned with the practical application of IoT sensor networks. It is unrealistic to think that non-technical actors looking to implement IoT into their workflows would build their own sensor devices. Finally, self-constructing these sensors would also mean ensuring they are water-tight and durable enough to withstand long periods of time outdoors in extreme environmental conditions. This represents a level of effort and risk too high for this thesis. Given all of these challenges, the decision was made to find a prefabricated alternative.

The most comparable research to the Kalterbachs GSN was done by AduManu 2020 which employed the Smart Water PRO device[2] from the company Libelium [3]. Unfortunately however, this device cost upwards of 1000 USD and therefore could not be considered for the network. In fact, any probe measuring dissolved oxygen saturation seemed to be prohibitively expensive and search was instead concentrated to find a sensor which would simply measure water height and temperature.

The Dragino Technology CO represented another popular choice and was used in several papers in the literature [50, 56]. This supplier provides a myriad of prefabricated sensors at an attractive price point. After some research on their website, the D20-LB/ D20S-LB – LoRaWAN Waterproof /Outdoor Temperature Sensor and the DDS75-LB LoRaWAN Distance Detection Sensor seemed to fit the requirements of the GSN at the Kalterbach. These sensors are waterproof, durable, and within the budget set by the stakeholders. This set of specifications fits all the needs of the GSN at the Kalterbach and eight temperature sensors and one height sensor were bought for the network. Two additional sensors of the same make and model were provided by the TUM as additional tests for the six month duration of the masters thesis.

[1] https://www.arduino.cc/
[2] https://www.libelium.com/iot-solutions/smart-water/

Table 3.1: *Summary of the two sensor types used in this GSN*

	Temperature Sensor	**Distance Sensor**
		
Name	LSN50v2-D20 – LoRaWAN Waterproof /Outdoor Temperature	DDS75-NB – NB-IoT Distance Detection Sensor
Sensor	Temperature probe for air, water, or object	ultrasonic distance detection with temperature calibration
Link	https://www.dragino.com/products/temperature-humidity-sensor/item/168-lsn50v2-d20.html	https://www.dragino.com/products/distance-level-sensor/item/301-dds75-nb.html
Battery	8500mAh Li-SOCl2 battery, 10 years of usage	8500mAh Li-SOCl2 battery, 10 years use
Range	-55℃ 125℃	280mm - 7500mm
Accuracy	±0.5℃ (max ±2.0 ℃)	±(1cm+S*0.3%) (S: Distance)
Price	58.19 €	81.10 €

3.3.2 Site Selection

In tandem to deciding on the actual sensor to use in the network, consideration had to be given to the locations for installation. The process of selecting appropriate and optimal sights for the sensors at the Kalterbach entailed several meetings with stakeholders and two site visits to understand the physical realities of potential locations. An initial meeting was held in April 2023 with representatives from Terrabiota, TUM, VDM, and two knowledgeable community members involved in fishing at and renaturation of the stream. This meeting was used as an introductory opportunity with information being disseminated broadly between stakeholders. At the end of this meeting, a tentative plan was suggested for sensor locations with the intention of planning a site visit to assess hypothetical feasibility.

With this tentative plan suggested, a site visit was then conducted to determine the practical feasibility of the locations. This was done in mid-spring and entailed a walk from the southernmost point to the northernmost point of the Kalterbach and back again; issues of installation were recorded and physical qualities of the selected locations were verified. We then came back together and opened up the conversation to a broader group of stakeholders to reflect on the original selections. This included the original group represented by Terrabiota, Verein Dachauer Moos, and the two local experts, as well as additional representatives from the Department of Water Economics in Munich (Wasserwirtschaftsamt).

After drawing up this rough draft, conversations were then expanded to include additional representatives from Terrabiota as well as individuals from the WWA. This proved extremely productive as the WWA especially could provide an additional technical perspective as well as place this network in a broader context; they helped to alert us to interesting statistical analysis they would hope to run on the data at a later point, how we could align the network design with these aspirations, and additionally ways this project could be used to potentially model future IoT applications at the WWA.

In the original network, we concentrated on a number of features along the Kalterbach, to measure how these modifications to the river changed the water temperature. The first stretch aimed to understand the impact of a fully shaded areas just north of the stream inlet, the second stretch aimed to measure the impact of a sunny stretch. Next, it was advised to look at the dragonfly windows which are characterized by a mixture of sun and shade and which stretch for a considerably long distance from around the kilometer mark 8.6 all the way down to 6.0. After this longer area, the next features of interest are the beaver dam, followed by two renaturation areas and then finally the water temperature at the end of the Kalterbach right before it flows out into the Amper.

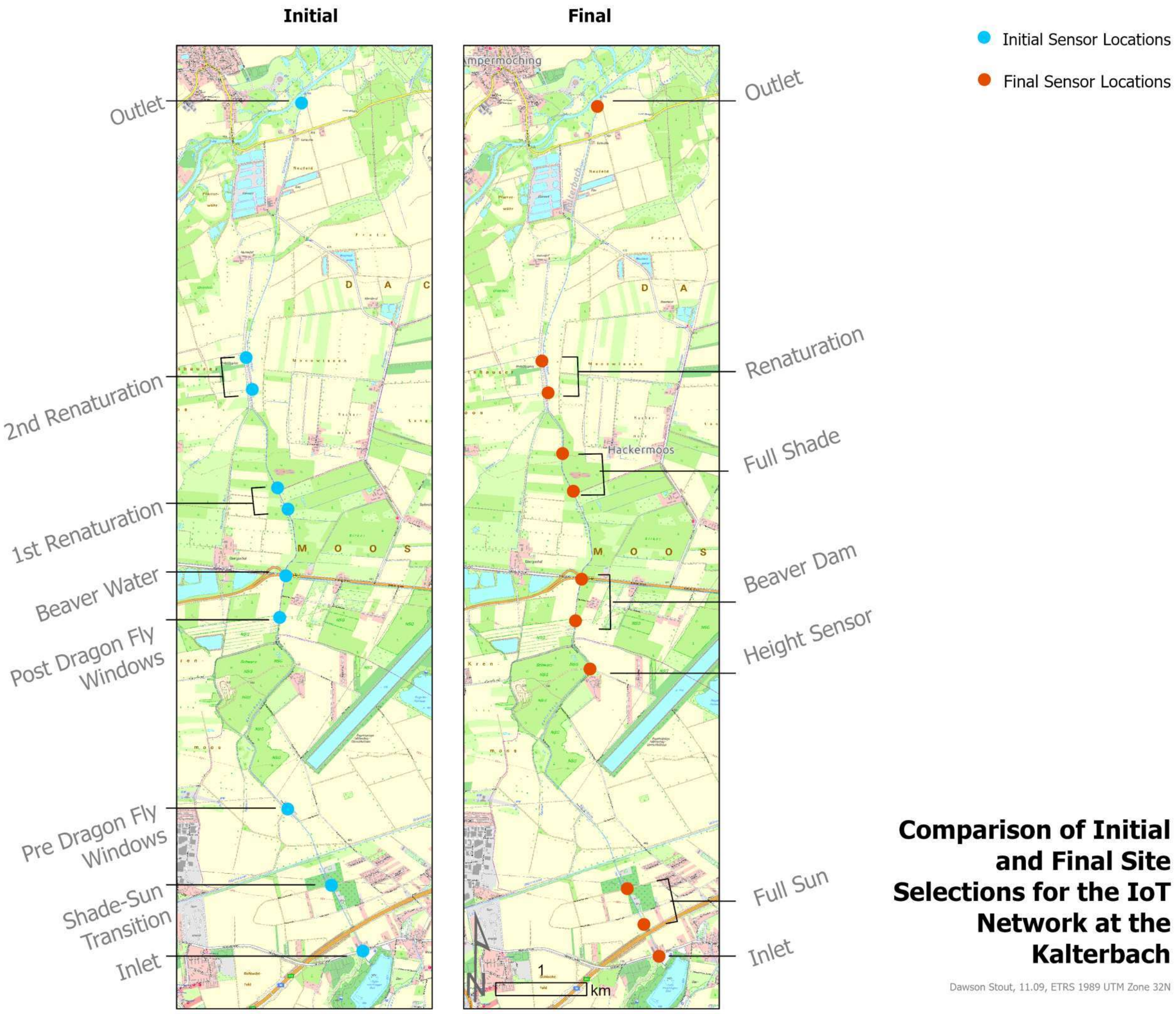

Figure 3.2: *Two iterations of the GSNs sensor locations demonstrating the evolution of the network as various stakeholders provided expertise and intention*

Upon further consideration however, it was concluded that changes had to be made to these original locations to optimize the quality and usefulness of the planned network. Firstly, the decision was made to standardize the lengths of the measured stretches as a point of parity across the Kalterbach. To facilitate comparison even further, the physical qualities to be measured were simplified and optimized. The basic focus was maintained with concentration still being given to the effects of shaded areas, sunny areas, the renaturation, and the beaver dam, however the locations for these recordings were altered slightly. In the original plan, two renaturation areas were selected, however this was later considered superfluous and instead we focused on the northernmost renaturation located between kilometer mark 3.0 and 3.4. This 400 meter stretch was established by the stakeholders as a good average distance to set up the sensors. The locations originally selected for measuring the impact of the beaver dam on the water temperature were deemed sufficient under these new standards and held at the mark 5.6 to 6.0. The shaded area which was originally placed at the southernmost point of the Kalterbach was modified and sensors were located from 4.2 to 4.6. This area was not only standardized to the 400 meter requirement, it also proved more consistently shaded than the southern section and further from the public who might interfere with the recording. Finally the sunny area was also moved to stretch from the 9.6 to 10.0 km mark. Here represented the sunniest stretch of the Kalterbach. Regarding the dragonfly windows, it was decided that these would not provide much useful analysis as the stretch is quite long and the percentage of shaded area at each window is variable. Instead, the 100 percent sun and 100 percent shaded regions acted as better benchmarks for analysis and therefore can be utilized for planning purposes later on. The original plan to measure the inlet and outlet points were still determined highly useful under this new plan and remained from the original.

Following these suggestions, the locations were updated and then once again a site visit was conducted to ensure the suggested locations could be feasible for installation. Finally, a pen ultimate version of the suggested points were sent to the previously mentioned stakeholders as well as land owners and relevant community members for revision; no further changes were made to the plan and we could move forward to the configuration and installation of the sensors.

3.3.3 Connecting Sensors to the Network

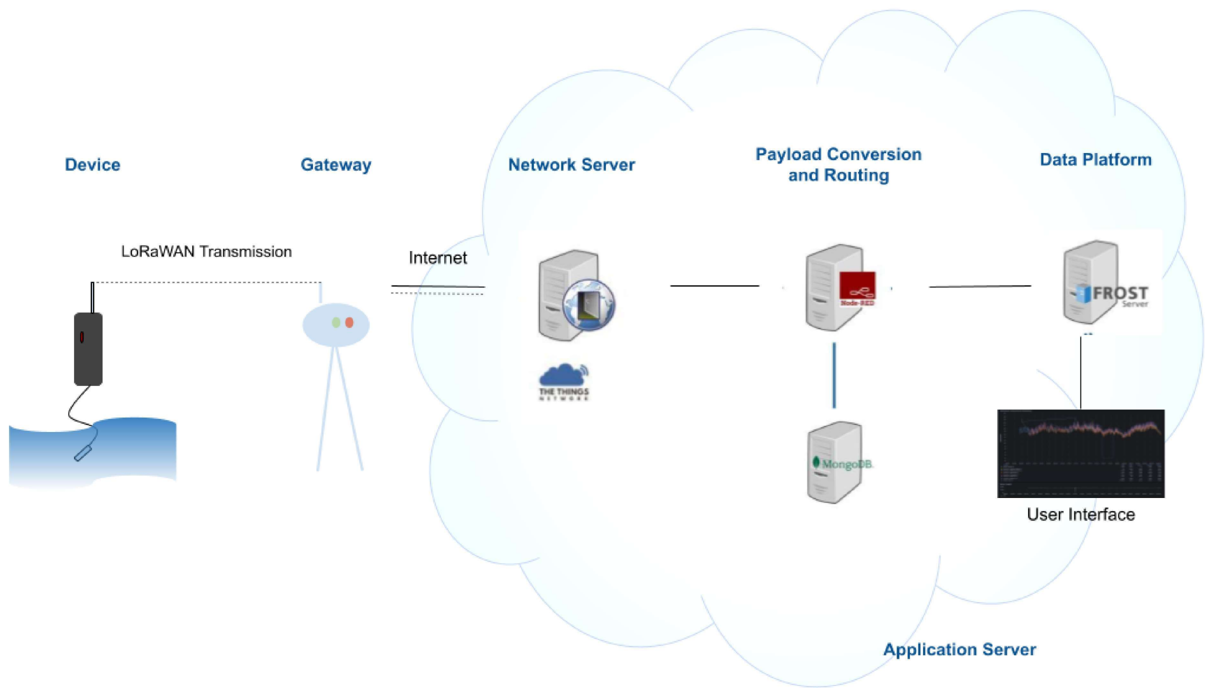

Figure 3.3: *Each uniquely identified sensor routes data through open-access gateways to the TTN server where it is then stored in the FROST server and accessible to the user*

While the sensors come completely prefabricated hardware-wise, they still need to be added to the network in order to send data. The observations being recorded from the devices must be organized and routed to a data platform if they want to be useful to the user. The route from the device to the user contains multiple steps and follows a standard workflow for the configuration based on the SensorThingsAPI (see Subsection 2.2.3); a tutorial of how to configure these devices according to those standards has been provided by the TUM for this thesis[3].

First the sensors have to be registered in the TTN server. Without this registration, the data collected at the sensors and then sent through to the gateways would not have an entity in the internet to arrive at. The server entity is built from the physical sensors by a series of codes which are uniquely paired to each hardware and imprinted in the transmitted signal. Once the sensor is brought online in the TTN server, a connection between the sensors, the gateways, and this server are established, allowing data to move from the field into the cloud. These gateways are set up by individual actors and then become part of the open source network. Sensors connect to gateways with the strongest connection which is usually mediated by proximity.

Network severs however do not store data. This is done in the application server, namely the FROST server in the case of this thesis. Anyone can establish a server for free with FROST; this thesis utilized a running instance of the FROST SensorThings API server which is part of the open IoT stack hosted and provided by the Chair of Geoinfomatics at TUM. The repositories of this IoT stack are open access and freely available online [4] [5]. In the case of this project, deciding on the already established TUM FROST server was logically and technically simpler, however, at any time, the entire Kalterbach project can be moved to its own unique server if deemed desirable.

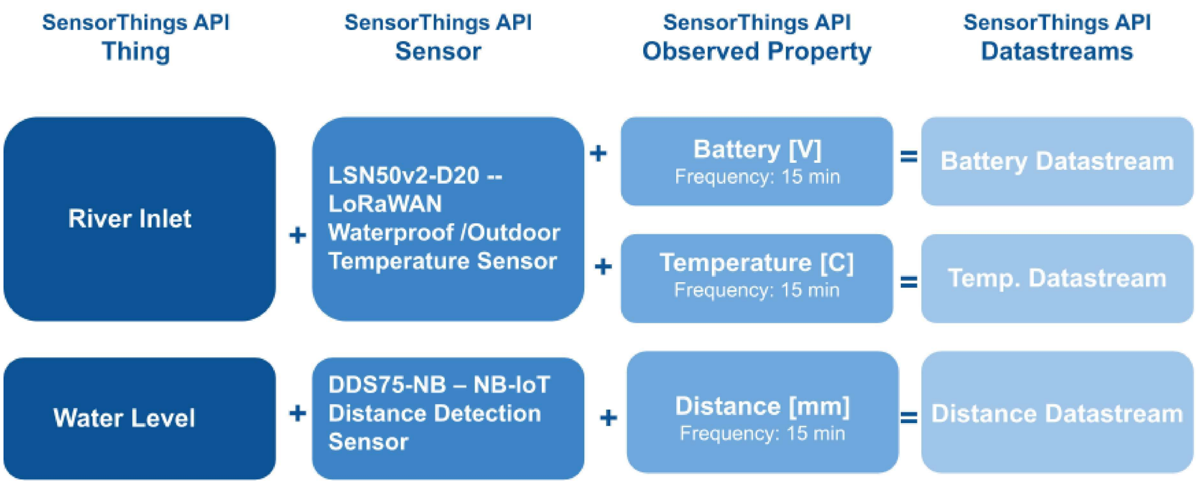

Figure 3.4: *The above figure exemplifies the process for constructing datastreams in the FROST server which identify where incoming data should be routed and stored*

Once an observation is received by the TTN server, the next step is to send that data point to a datastream within the FROST server for long term storage. Datastreams are created under the SensorThings API standard and require several pieces of information to be established; this information helps to create a storage location unique to each sensor device and observation type which prevents confusion with other incoming data and keeps everything organized. The main data set we are interested in collected is on water temperature at various points as well as the water height in the case of the distance detection sensor; an auxiliary data set is on battery life of the devices. Figure 3.4 outlines how datastreams are created in the FROST server. Initially, the three entities (sensor, thing, observed property) were defined as JSON objects in this FROST server. Nine unique "things" (8 associated with locations for water temperature measurements, one associated with the water level) were created in the FROST-server using the identifier key for each physical device. The "sensor" entity referred to the two types of sensors

[3]https://wiki.tum.de/display/geosensorweb/FROST+-+Tutorial
[4]https://github.com/tum-gis/tum-gis-iot-stack-basic
[5]https://github.com/tum-gis/tum-gis-iot-stack-k8s

used in this project (i.e. the distance detection sensor and the temperature sensor). For each device, two observed properties are always recorded - the first is the battery voltage, the second is the distance in mm or the temperature in C respectively.

From these building blocks, unique data streams could be created which identified and organized the measurements coming from individual sensors. When creating these entities, additional information can be inputted such as location and transmission frequency. For this thesis, coordinate locations were estimated using Google Maps and a transmission frequency of 15 min was decided. A more frequent a recording would be unnecessary for the purpose of detecting water temperature changes; any lower however might encounter the issue that data could not be sent regularly given a weak signal connection. The open-source, java application FROST-Manager[6] helps to manage previously established entities in the FROST server. While this is a GUI tool, the entities can still be entirely created using the web interface provided by the FROST server or using HTTP POST requests. For the purposes of this thesis, this tool was used to update sensor names and locations which may have changed over the course of the installation.

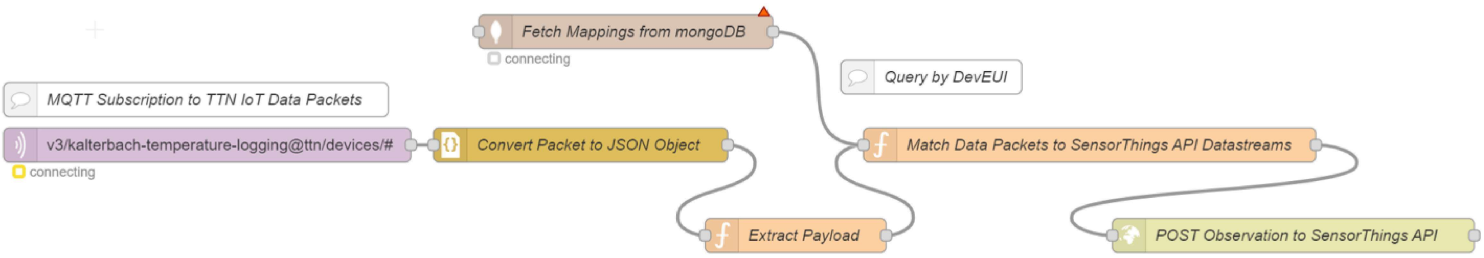

Figure 3.5: *A simplified workflow showing the streaming of TTN messages using MQTT, extraction, transformation, and loading to SensorThings API using Node-RED*

Upon establishing sensor entities within both the network (TTN) and application (FROST) servers, the need arises for these entities to establish connection between them. IoT devices, often operating under resource constraints, necessitate the encoding of incoming data to facilitate efficient data transmission. In this context, the thesis leveraged the Cayenne Low Power Payload (LPP) format, a lightweight and efficient payload format widely employed in the IoT sphere to transmit sensor data across diverse communication protocols. At the core of this communication infrastructure lies MQTT, a messaging protocol crafted to optimize data transmission from battery-powered IoT devices with limited resources. MQTT standardizes the encoding of sensor readings and device data into a compact format, thereby reducing transmitted data while preserving essential information.

Node-RED[7] played an instrumental role in orchestrating this communication and data processing, acting as an intermediary to facilitate the connection between the network and application servers. This visual programming tool streamlined the routing of sensor data, its transformation into Cayenne LPP format, and its subsequent transmission via MQTT. Figure 3.5 is a screenshot from NodeRed showing this entire workflow and visualizes how each of these components are networked together to finally bring a sensor online. Essentially, Node-RED served as the bridge that streamlined the flow of sensor data between the network and application servers, enhancing the system's efficiency and effectiveness.

[6]https://github.com/FraunhoferIOSB/FROST-Manager
[7]https://nodered.org/

```
{
    "_id": "s_beaver",
    "name": "South of Beaver",
    "dev_eui": "A84041DDE1xxxxx",
    "datastreams": [
        {
            "lpp_id": 1,
            "sta_servers": [
                {
                    "sta_url": "https://gi3.gis.lrg.tum.de/frost/v1.1",
                    "datastream_iot_id": 720
                }
            ]
        },
        {
            "lpp_id": 3,
            "sta_servers": [
                {
                    "sta_url": "https://gi3.gis.lrg.tum.de/frost/v1.1",
                    "datastream_iot_id": 772
                }
            ]
        }
    ]
}
```


Figure 3.6: *MongoDB JSON code mapping the TTN Server to the FROST server for the South of Beaver sensor*

Linking the TTN and FROST servers is MongoDB, a NoSQL database management system. This system plays a crucial role in mapping the LPP channel numbers assigned to the sensor data to the corresponding datastreams within the FROST server and associates them with the device ID. This mapping process ensures the accurate ingestion, processing, and availability of data for analysis, visualization, and decision-making through the SensorThingsAPI. In figure 3.6, a MongoDB mapping for the sensor south of the beaver dam is provided. the "dev-eui" holds the unique identifier for the device which was used to register the device in the TTN server. Encoded under the "lpp-id" we see the two data streams (battery, flagged as 772, and temperature, flagged as 720) created for the device in the FROST server. With this data properly mapped, information can reliably reach the FROST server and data can be correctly routed to the previously established datastreams. When these datastreams are queried and examined in a visualization program, such as Grafana, historical data becomes accessible and can be tailored to individual requirements

3.3.4 Sensor Installation

With the sensor encoded and mapped, they could then be taken to the field and installed in the locations agreed upon in our previous stakeholder engagement. The installation period took place from the end of May through to the end of July, however most of the sensors were successfully in the water and recording temperatures by the middle of June. Sensors and tools for installation were usually biked or hiked into the measurement point and the farm of Obergrasshof was used as a home-base of sorts where things could be more easily accessed.

The installation represented room for practical creativity as previous studies provided little to no explanation on how sensors were placed in the field; additionally, even had this direction been provided as a reference, each location on the Kalterbach presented a unique terrain, climate, and surroundings which made strict procedure impossible. Instead, installation at each point had to be evaluated independently on site. Generally, the sensors were installed by zip-tying them to vegetation, drilling them onto dead trees or wood posts, or, in some cases- by screwing them to a wooden board and then using epoxy glue to fasten them vertically on concrete. In the case of the temperature sensors, the temperature probe was fastened to a metal stake which was hammered into the river bed to ensure that the probe itself would always be submerged. Care was taken to ensure the probe did not touch the metal of the stake and was instead free floating in the river. Regarding the water height monitor, for this installation, the device was mounted in the middle of a bridge and then the ultrasound sensor had to be fixed to the sensor perfectly perpendicular to the river surface. After the sensor probe was in place, the distance from the height sensor probe to the river bed was recorded using a ruler and used as the 'fixed distance' (see figure 3.7 in section 3.4.4).

When deciding on the local location of the sensor, certain criteria had to be managed. Firstly, concern was given to potential vandalism of the devices - if a local were to see these new futuristic looking devices strewn across the forest, they would naturally become interested and explore. To prevent damage to the devices, the sensors were placed in somewhat hidden areas - behind a tree, in a bramble, generally out of sight. Additionally, a small tag was placed alongside every sensor which briefly explained its purpose and who to contact with questions and concerns. Originally it was considered to fasten the sensors in place with metal zip ties or band, however, this was later deemed an unnecessary expense given the remoteness of the devices.

While covertness was one wish in this installation, another, more important requirement was adequate connection and oftentimes there existed a tradeoff between these two objectives. The signal between the sensors and surrounding gateways can be hyper sensitive and vary greatly even within a few centimeters. If a sensor was close to the ground or hidden in a bush, the signal may become obstructed and this limits the quality of the data. To help understand the connectivity at various locations, a test device was brought along during the installations as a way to find a reliably high connection. While this provides a fine estimate of the signal at a given spot, this is also dependent on time and climatic conditions - as such, sometimes the only way to reliably know if a given sensor will be able to send observations is to place it and wait a few days. This naturally makes planning of a project a difficult task and contributes to the long period of installation. Some sensor locations had to be visited several times and fidgeted with ever so slightly to establish a connection.

3.4 Data Processing and Visualization

3.4.1 Grafana

The web-based data dashboard Grafana was employed to interactively visualize and organize the data streams from the network. This open-access application is a user friendly and effective tool for operability with IoT data. Attractive dashboards can be created and are easily interpretable to a wide audience. Possible dashboards include time series, maps, bar charts, gauges for battery readings, and heat maps, to name just a few. Users can either directly engage with the data in Grafana or, for more complicated requests, using JSON paths and queries. While simple requests are straightforward and user friendly in the Grafana dashboard, more complex queries are not always clear and require more software understanding. The FROST server was directly connected to dashboard using a plugin in Grafana [8].

[8] https://grafana.com/grafana/plugins/iosb-sensorthings-datasource/

```
https://gi3.gis.lrg.tum.de/frost/v1.1/Things
$filter=startswith(properties/project,%27Kalter%27)&
$expand=Locations,Datastreams($select=name; $expand=Observations($select=result,
    resultTime,phenomenonTime;$orderby=phenomenonTime%20desc;$top=1))
```

Listing 3.1: *HTTP GET request URL which delivers data used to create the map in the Grafana Dashboard*

The above URL illustrates how data can be filtered according to the SensorThings API. This link specifically was used to create the map part of the dashboard, hence the need to filter both location and most recent observation. This link filters all the "Things" which are under the custom property defining the entire project of the "Kalterbach." It is filtered by identifying all custom properties that begin with "Kalter..". It then expands the linked "Locations" and "Datastream" entities as well as the "Observations" for these Datastreams. From here, the "Result", "resultTime" and "phenomenonTime" are selected and then ordered using a descending timestamp and only selects the first one, (i.e. the latest observation.) The HTTP GET request can be structured as JSON query (shown in Listing 3.2) and input into the Grafana system. This output then can be used to create an interactive map which changes as new data is delivered from the network. In addition to this map, the dashboard for the Kalterbach has several visualizations including a time series graphic for all temperature sensors, battery gauges showing the real time battery life, and a time series for the distance sensor. The querying for these dashboard elements are more automatic, point-and-click processes and, unlike the more complex map, did not require a unique query to be established.

```
$.value[*].name
$.value[*].Locations[*].location.coordinates[0]
$.value[*].Locations[*].location.coordinates[1]
$.value[*].Datastreams[*].Observations[*].result
```

Listing 3.2: *Unique JSON Queries responsible for creating a map visualizing the sensor values and their locations*

3.4.2 Temperature Variation along the Kalterbach

While the real time data provides an important tool for monitoring of the river and surveillance of the data by the project managers, it provides a rudimentary understanding without securing a deeper, mathematically backed insight into the trends behind the data. To investigate the data further, statistical analysis was conducted on the timeseries.

Principally, stakeholders were motivated to create this GSN in order to have a clearer impression of the temperature change of the Kalterbach from north to south. Where along the stream is the temperature increasing, where is it decreasing? How does that look throughout the course of the day? When does it warm, when does it cool? To answer this, we begin by understanding temperature trends at individual points on the river measured by individual sensors. For a given period of time (ex. A two week hot period in August), all temperature observations were plotted as a function of hour of the day (i.e. from 0:00 to 23:59) and then the average for each hour calculated. This graphic allows for warming and cooling trends at individual points across time to be understood.

The next step was to visualize this data in the context of the entire sensor network, thereby deepening our understanding of landscape interactions at the stream. From the hourly averages, an aggregation in 8 hour intervals for every sensor in the network was conducted (i.e. 0:00-8:00, 8:00 - 16:00, etc.) and these values were identified as the morning, day, and evening averages.

From these averages, an interpolation was conducted for every meter along the Kalterbach using a Piecewise Cubic Hermite Interpolating Polynomial (PCHIP) [22]. This interpolation method provides a smooth connection of points while avoiding the issue of overshoot making it ideal for this relatively small data series. With these interpolated values calculated, they could now be subtracted from the average temperature of the stream for the entire period in question, outputting either a positive or negative change in degrees. This value was then plotted as a function of distance from the outlet of the Kalterbach and three plots for each 8 hour period were made. The result is a comprehensive visual showing both the temperature change as a function of time of day as well as distance along the waterway.

3.4.3 Climatic Variability and Water Temperature

The central question which originally spurred investigation into IoT at the Kalterbach centered around the impact of increased solar radiation on the stream as a result of the dragonfly windows along its banks. The incoming data from the GSN becomes instantly more powerful when contextualized within the vast world of data characteristic of this, the era of internet. Weather data was merged with this network's data to provide a deeper insight into the dynamic, environmental interactions at the Kalterbach.

Firstly, the data had to be cleaned and aggregated in order to be made useful. Given the strong daily periodicity of the time series, the first task was to collapse it down into a more manageable daily average. However, although wireless sensors have generally good signals, like everything in life, they are not without their lapses. While the devices were coded to take a measurement every 15 min, sometimes the device can go extended periods offline. As such, when trying to understand the data in the context of a day, one might not always have the relevant means. In calculating the daily mean value, all days with less than three data points were immediately identified as insufficient and recorded as N/A in the aggregated set. After the insufficient days for each data series were identified using this method, a difference could be calculated between various sensors. In addition to the total change from the stream inlet to the stream outlet, three additional areas of interest were identified as useful to investigate for their impact on water temperatures. From north to south, these were the beaver dam, shadow area, and renaturation area. The difference between daily averages for the sensors north and south of these areas of interest were calculated to give the total change attributable to each landscape.

After determining the average change in water temperature for these four features (entire stream, beaver dam, shadow area, and renaturation), the daily difference data for each area was then matched to weather data on daily sun hours. This data was taken as an average value from the three weather stations which triangulate over the Kalterbach and which was downloaded from the German Weather Service (*Deutscher Wetterdienst*)[9]. Then, the daily sun hours were merged to the daily average temperature difference. This merger allowed for filtering to see the impact of high sun versus low sun days in accordance with the original concern of the project to understand the impact that clearing trees and other shade giving vegetation had on the warming of the river water. To visualize this impact, two figures were produced. The first was a box-and-whisker plot filtered in three ways: the first displayed all the data, the second only included days with less than 5 hours of sun, and the third all days with more than 5 hours of sun. In addition to this graphic, the second visualization was a simple correlation graph which laid sun hours against temperature difference. In this way, the temperature data can be viewed in the context of the weather and any strong impact of solar irradiation on changes in water temperature can be linked.

[9] https://www.dwd.de/EN/ourservices/cdc_portal/cdc_portal.html?nn=24736

3.4.4 Water Height, Discharge, and Flow Velocity

Under the query scheme designed for the Grafana visualization, mathematical manipulation of the incoming observations was not possible. As such, several equations were run on the incoming data from the distance sensor to output the water height, discharge, and flow velocity.

The raw data coming from the sensor named ‘Water Height’ was simply a measure in millimeters of the distance from the ultrasonic distance sensor to the surface of the water below. To get the actual water level in the stream at a given timestamp, the distance from the river bed to the sensor had to be accounted for. As seen in figure 3.7, the original ’fixed distance’ was manually measured the day of installation and then used to calculate the height from the sensor to the river bed. The incoming data from the height sensor (’variable measured value’) was then simply subtracted from this fixed value to calculate the water level.

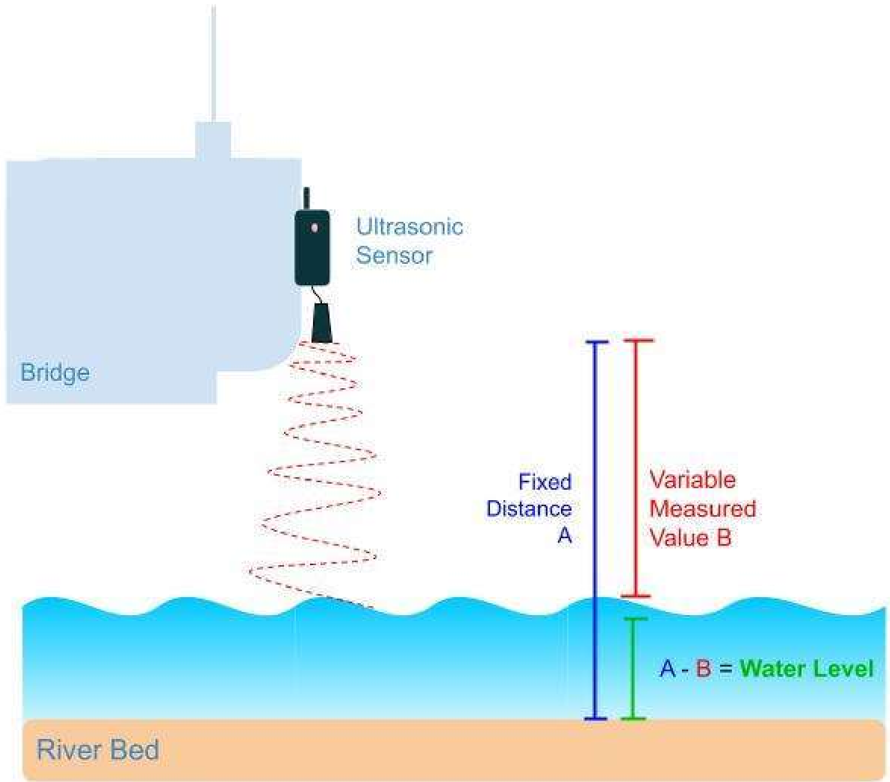

Figure 3.7: *Cross-section of the installation of the water height sensor and values manipulated to determine the water level*

More interestingly, the stream discharge and mean flow velocity were also calculated from this distance sensor. The calculation for the mean flow velocity is given from the Manning-Strickler formula [26]:

$$V = k \cdot R^{2/3} \cdot I^{1/2}$$

With V equal to the mean flow, k is Stickler coefficient or the roughness parameter, R the Hydraulic Radius, and I is the gradient of the river bed. k was chosen from a list of potential values which was developed by Chow in 1959 [17].The roughness parameter has a large influence on the final outputted values and under ideal circumstances would be calculated in the field for the stream. Since this was not possible, however, Chows Table allows one to estimate a k value based on the physical characteristics of the waterway in question. The Kalterbach was identified through collaboration with stakeholders from Terrabiota as a “main canal" that is "clean, straight, full stage, no rifts or deep pools" and "some weeds and stones." Normally, given these characteristics, a value of 29 $[m^{1/3}/s]$ would be ideal, however it should also be considered that the Kalterbach is a very small water body. Because of this, the ratio of water volume to surface area of the river banks is smaller as per the scaling law. Previous work has identified that, for such small water bodies, a much smaller roughness parameter should be chosen [36]. As such, through consultation with Terrabiota, the Chow table estimate was halved to be 15 $[m^{1/3}/s]$ for k. The gradient I of the river bed was determined remotely using a digital elevation model from the Copernicus Land Monitoring Service[10] in arcGISpro as 0.0037. R is the value that will constantly be had to be calculated from the time series data and is given by:

$$R = \frac{A}{U} = \frac{b \cdot h}{b+2h} = \frac{b \cdot (d-x)}{b+2(d-x)}$$

The value b is equal to the length of the river, evaluated from satellite images as 5.2 m. The value for h refers to the water level and was determined from the changing values of the timeseries. For this, first the fixed distance d from the sensor node to the river bed was measured on site as 1.934 m. To calculate h, all that needs to be done is subtract this value from the time series data x. After we have determined R, we can now solve for the mean flow V with the most fundimental values:

$$V = k \cdot \left(\frac{b \cdot (d-x)}{b+2(d-x)}\right)^{2/3} \cdot I^{1/2}$$

After solving for V, the discharge Q could finally be determined simply by multiplying the mean flow velocity by the area (also changing with each timestamp):

$$Q = V \cdot A = V \cdot (b \cdot (d-x))$$

With these equations and variables defined, observations on water height could be downloaded, and the CSV file fed through a python script. The average height, flow velocity, and discharge were output into a table for each month with available data.

3.5 Project Assessment

An important part of this work is to understand the practicality and utility of IoT in a novel application and for a novel group of stakeholders. Principally, we are interested in the transfer of GSNs from theory into positive and helpful practice. This thesis can be seen as a pilot project off which other applications can springboard. Therefore, a paramount task is to identify challenges, lessons learned, potential pitfalls, and outcomes which would benefit or hinder future use; The adoption of any technology takes time and is not without hindrances, the least we can do is identify these and note them for the benefit of others.

Several frameworks exist for project evaluation and this thesis employs two standard methods to document and structure its reflection. The first is Lessons Learned. The Lessons Learned framework for project evaluation is a systematic approach to capturing, analyzing, and applying knowledge gained from the experiences and outcomes of a project. It involves identifying and documenting both successes and challenges encountered throughout the project lifecycle, with the goal of improving future projects and enhancing overall organizational effectiveness. Typically this framework involves data collection throughout the course of the project's life with project milestones being used as a moment for reflective analysis and review. For this thesis, throughout its implementation, notes have been taken on major challenges and success with exemplary events precipitating these outcomes also documented. These have then been organized in a tabular format which then reflects on the impacts of such events, the workarounds, and the

[10] https://land.copernicus.eu/en

future recommendations. Additionally, in good participatory fashion, these Lessons Learned were then given to various stakeholders and asked for their feedback and insights. Including as many relevant stakeholders as possible allows a broader picture of the project's success to be patched together. This addition of diverse perspectives is crucial for the continued functioning of the project, especially as it evolves form a research project primarily spearheaded by the TUM, to one taken on by the Verein Dachauer Moos.

From this first analysis, a SWOT Analysis was then conducted. A SWOT stands for Strengths, Weaknesses, Opportunities, and Threats. This framework allows you to assess the internal and external factors that influenced the project's outcomes. It helps identify what worked well (strengths), what didn't work well (weaknesses), potential avenues for growth (opportunities), and external factors that might hinder future success (threats). By taking the Lessons Learned as the starting point for this analysis, we are provided a robust set of reflections which organize our thoughts and energies. The analysis allows for goal making and can inform the development of strategies that leverage important aspects of the project in the future.

Project evaluation plays a pivotal role in determining the ultimate success of an initiative. This significance is particularly accentuated when engaging with non-technical stakeholders and given the university's involvement extends only to the end of the 6 month window for the thesis. The assimilation and analysis of project experiences, successes, and challenges serve as a valuable knowledge that can be harnessed by subsequent project managers. These insights extend beyond the immediate context, facilitating a more informed approach to future endeavors.

4 Results

4.1 Stakeholder Mapping

4.1.1 List of Stakeholders

At the start of this thesis, research and interviews were conducted to understand the social networks and various stakeholders responsible for the governance of the Kalterbach as well as their roles in the installation of the GSN. By understanding this web of relationships, the project could more effectively be implemented and a framework for the project requirements could be generated. A list of the myriad players and a description relevant to the Kalterbach in have been compiled here:

Table 4.1: *Stakeholder Information*

Stakeholder	Description	Role on the Kalterbach	Role in this GSN	Website
Verein Dachauer Moos (VDM)	Local organization supported by the surrounding municipalities (kommune) which has taken on several projects in and around the wetlands to support biodiversity and healthy ecological functioning	Responsible for the conception of the “model project for the renaturation of the Kaltbach.” Has carried out several other rehabilitation projects around the area.	Directs funds for buying the sensor and associated installation materials. Has ultimate say in where sensors should be installed. Maintains the sensor network upon completion of this thesis.	https://www.verein-dachauer-moos.de/
Terrabiota	Ecological Engineering firm with many years experience in renaturation in and around Bavaria	Technical Lead for the project beginning in December 2023. Providing technical knowhow for effective decision making at the Kalterbach.	Initiated the idea to use GSN in this project. Will assumedly use the collected data to inform future decision making in how to renaturalize the Kalterbach.	https://www.terrabiota.de/#start
TUM	Foremost University in Europe. Specifically involved are the Chair of Geoinformatic and the Chair of Land Management and Geospatial Science		Responsible for the evaluation of this thesis, IoT infrastructure, and therefore the GSN as a whole. Provides the technical expertise necessary to install the sensors. Directs the epistemic development of this technology in the given use-case.	https://www.asg.ed.tum.de/gis/startseite/ https://www.asg.ed.tum.de/bole/ueber-uns/team/

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Table 4.1 – Continued from previous page

Stakeholder	Description	Role on the Kalterbach	Role in this GSN	Website
Water Management Office or the Wasserwirtschaftsamt Bayern (WWA)	Bavarian State Agency responsible for the protection and proper use of water and water bodies within the Bundesland	Legislatively, the Kalterbach is under this authority under the Water Framework Directive.	Provides technical support to conceive the hydromorphological renaturation of the stream. Regular exchange between WWA, Terrabiota, and the VDM to ensure a positive outcome at the Kalterbach. Provides technical advice on where to place the sensors as well as the future potential of such a network. Highly interested in the use of these sensors for application in other areas.	https://www.wwa-m.bayern.de/
Local Municipalities	The neighboring Municipalities (kommune) around the stream. Municipalities include: Dachau, Oberschleißheim, Herbertshausen, Karlsfeld, München	Hold legal and administrative rights over the waterway and share its governance. Direct funds to projects happening at the Kalterbach.	Provides the funding for the Model project to renaturalize the Kalterbach, but does not direct the funds.	
Farm at Obergrashof	Organic farm, educational center, and community through which the Kalterbach runs through	First renaturation projects were largely and unofficially initiated by Obergrashof. Has deep ecological knowledge on the Kalterbach.	Logically important for storage of the sensors prior to installation as well as for providing materials for installation.	https://obergrashof.de/

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Table 4.1 – Continued from previous page

Stakeholder	Description	Role on the Kalterbach	Role in this GSN	Website
Fishers (Fischern)	Several individuals have fishing rights at the Kalterbach and these fishermen play an important cultural and knowledgeable role	Use the Kalterbach regularly for fishing and play an important cultural role. Consulted by VDM and others for ecological knowledge.	Have immense ecological knowledge on the site, invaluable in understanding dynamic interactions at the Kalterbach and directing the project to measure at the right points along the stream. Help to maintain the network upon closure of this thesis.	
Farmers and Landowners	Families and individuals who own land through which the Kalterbach flows	Own lands around the stream. Land use practices (e.g., application of fertilizer) impact the river ecosystem.	Must be consulted when installing the network on or around their private land.	
Residents near the Kalterbach	Families, individuals who live, work, and play around or at the Kalterbach	The Kalterbach offers an important place of identity and recreation.	Potential interest in the project. Immediately aware of any sensor installed in the stream, potential for tampering with the devices.	

4.1.2 Power-Reference Matrix

With these stakeholders identified and an outline of their role at the river clarified, these players could then be mapped visually on a Power-Reference matrix as a visual means of conveying responsibility and relation to the installation of our GSN . While this graphic is based on subjective weighing of influence and interests, it is helpful for scaffolding thinking and approaching the project.

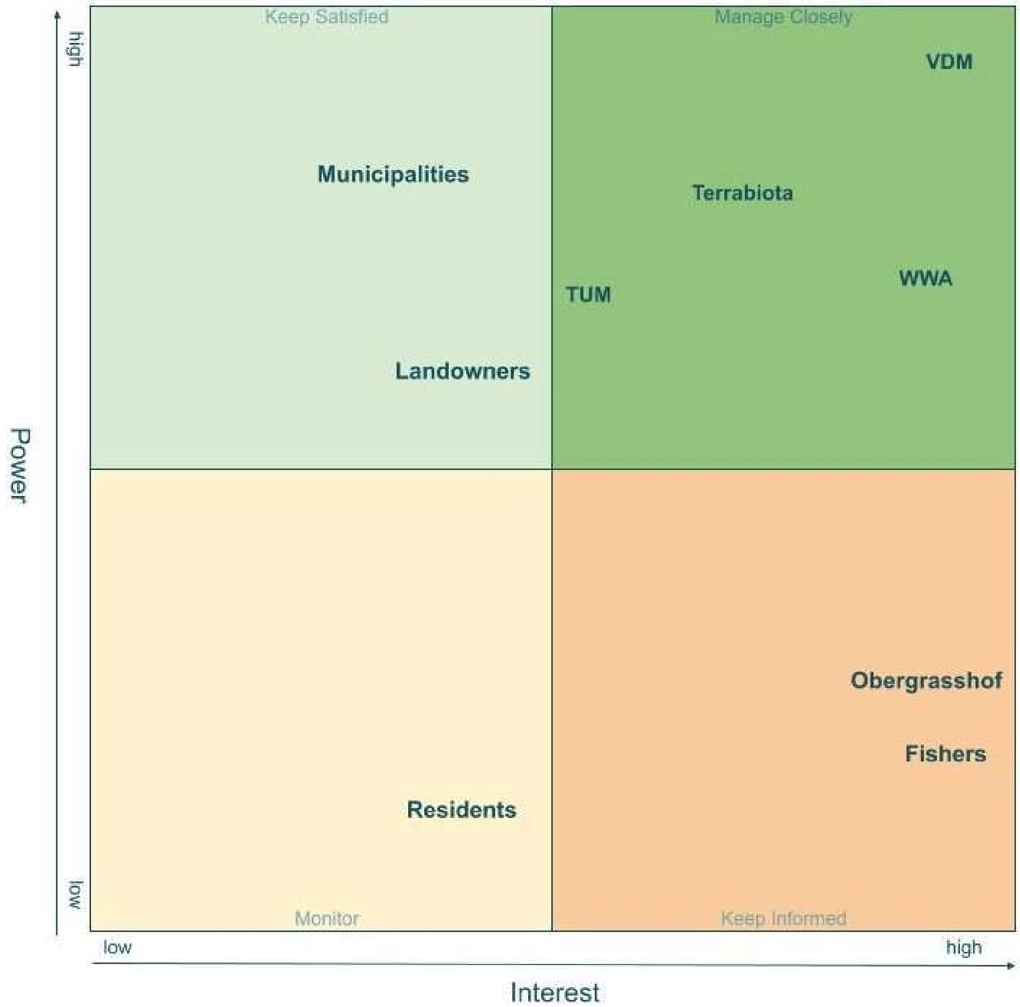

Figure 4.1: *Visual representation of the relevant stakeholders according to their power and interest in the GSN at the Kalterbach*

From the matrix, we see VDM, WWA, and Terrabiota emerge as the most critical players involved in the success of the GSN at the Kalterbach. These stakeholders are responsible for the funding of the sensors and later use of the data. Ensuring they understand and agree with the GSN proves critical to its functioning. The TUM - necessitated by its responsibility in providing a grade for this thesis - also plays an important role here; However, even grades aside, the TUM would be a powerful player given its technical know-how of the sensors. There remains a vested interest in the outcome of the network as a proof of concept of IoT technology, Open standards, and GSNs in this open-nature, environmental monitoring use cases. Obergrashof and the fishers along the river have a high amount of interest in this project - and as such offer extremely valuable knowledge resources - however do not have a great deal of sway in deciding specific details of the project. Addressing the top left corner, the surrounding municipalities and landowners represent important players only if major disagreements arise from sensor installation, trespassing, or other points of conflict and therefore should simply remain satisfied with the project, being informed when necessary to avoid disputes. Finally, local residents have little sway in the project details, although may have more interest given a personal connection to Kalterbach. The primary concern from residents is tampering with the device, although they could represent a positive potential for the network as a resource to tap into for voluntary reporting when devices are broken or damaged.

4.2 Network Installation

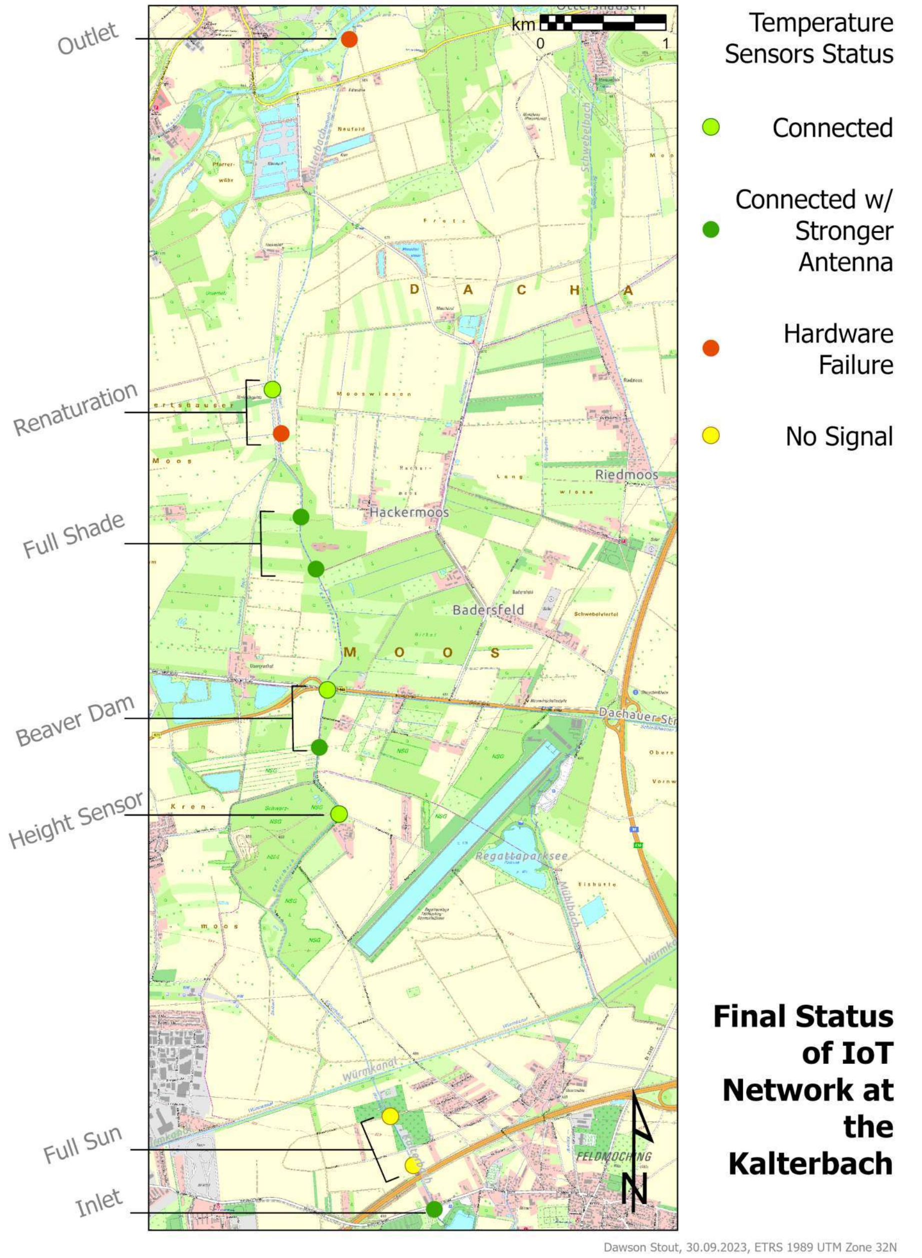

Figure 4.2: *Status of the sensors receiving and transmitting data in the water*

At the time of completion of this thesis at the end of October, there were 6 sensors regularly collecting data on the water temperature of the river. For a period of about 4 months, two additional sensors were successfully brought online, however these experienced hardware malfunctions and therefore had to be taken offline. The installation took longer than expected and lasted from the end of May through the month of June and into the beginning of July. Finding a location which had a strong signal proved a difficult task that required leaving the sensors in the field for a period of time, monitoring the strength of the connection, and adjusting the sensor later if need be. The six sensors that are still sending data do so at intervals regular enough to observe a day-night periodicity and clear trends in temperature when observed at larger time periods. Not all sensors have the same regularity of data transmission however. This signal strength is a confluence of both location on the river as well as whether they have aftermarket antennas attached to boost the connection.

Four of the eight temperature sensors required a more powerful antenna to receive any signal at all. These sensors include the river inlet, the point south of the beaver damn, and the two sensors in the "shadow area." In this shadow area, the dense tree cover probably increased disrupted the signal, thus requiring a boost with additional hardware. At the south of the stream, just above the Feldmochingersee, the connection to any gateway was extremely weak. Both of the aspired points in the 'Full Sun' area of interest could not successfully be connected to the network even after adding the stronger antenna. This said however, the aftermarket antennas generally added a great deal of signal reliability to the sensors - even more so than probably necessary as both the 'river inlet' and the 'south of beaver' exhibited some of the most reliable connections after the addition. Moving northward, the signal increased in strength and generally, sensors on the norther half of the Kalterbach were less likely to stop sending data randomly or send at irregular intervals. The water height sensor had probably the strongest signal of all the sensors, probably due to the fact that it was attached high on a bridge without any obstruction from the sky above.

The two sensors which experienced hardware malfunctions were taken offline for the following reasons. At the sensor south of the renaturation area, the tree that it was attached to was blown over in a strong storm and the sensor fell into the water, causing it eventually to fill with water and no longer be viable. The sensor at the river outlet also was taken offline, however this was due tampering with the device from wild animals. Three times over the course of this thesis, animals bit through the sensor probes and caused hardware issues. These probes could be replaced as there were spare parts. The sensor at the river outlet was bit through and the temperature probe was replaced, however the second time this happened, there were no additional temperature probes to act as a replacement. Additionally this happened at the end of the study period and time constraints did not allow for the repair to be completed. Theoretically, the sensor itself still works and can be brought online again if investments are made to buy another probe. These instances highlight a major challenge of open nature environmental monitoring - ensuring durable hardware.

4.3 Data Processing and Visualization

4.3.1 Grafana

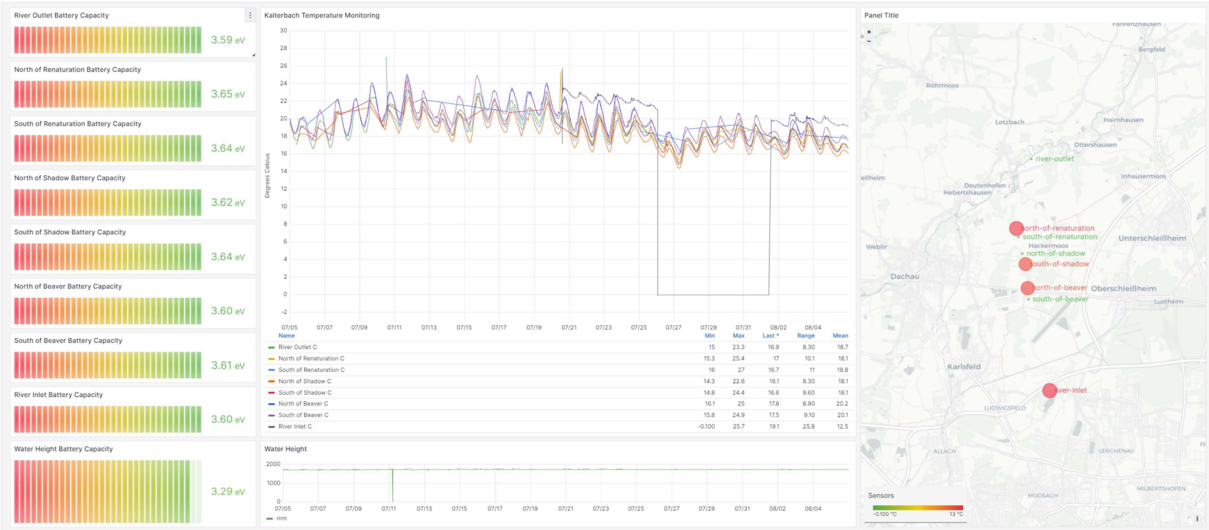

Figure 4.3: *Example of how the dashboard for the GeoSensor Network at the Kalterbach is displayed on Grafana*

With the sensor network successfully transmitting data, the incoming datastreams could be routed through and visualized on the open source platform Grafana. The FROST server can connect to this dashboard application through an internal plugin optimized to receive data under the SensorThingsAPI standards. A screenshot of the main dashboard has been included below. This display includes the battery status in electronvolts for all the 9 sensors on the left most side, a time series graph for both the water height sensor and the eight temperature monitors (displayed in the middle panels), and finally, on the right, a map showing the locations and last recorded temperature for each of the temperature sensors.

The right most 'Map' panel provides a mixed visualization showing both the last measured temperature as well as the location of all temperature sensors at the stream. This visualization provides extra context to those looking to understand water temperature at the Kalterbach; when scrolled over, the pop up window shows information on the temperature last recorded at this sensor and the time of measurement. A limitation arises with this visualization however if a sensor remains dormant and not sending for long stretches of time. The viewer does not get a clear understanding of changes in water temperature across the course of the stream under these sporadic data transmission conditions.

Figure 4.4 shows a more detailed time series of the water temperature sensors. this data paints a picture of the happenings at the Kalterbach over this period from June to September. After the sensors were connected, an immediately striking phenomenon is the abrupt dips and spikes that affect several of the sensors later in the summer. At the 'river inlet' (purple), the 'river outlet' (green), and the 'south of renaturation' (light blue) all the sensors suddenly drop to 0.1 for an extended period of time. This data pattern came to be understood as indicating a hardware malfunction with the sensor probe. In the first case at the ' river inlet' we discovered an animal had bitten through the sensor probe, causing null data to be sent through. This probe was replaced and protected by threading the thin rubber probe through a piece of firm plastic watering hose. Unfortunately, this protective measure was only included for the other sensor in the network after the second such case occurring at the 'river outlet.' After replacing this second temperature probe, all the sensors were outfitted with such a covering. Unfortunately however this did not stop all animals from tampering with the devices and the outlet sensor once again fell dormant just a few days after the initial repairs.

The other case of a hardware failure occurring at the 'south of renaturation' was not a care of animal interference, but rather a weather incident. A large storm blew over the tree to which this sensor was attached and ripped the probe off from the node. The node then fell to the water and although was able to remain watertight for about a week, it eventually leaked water and the node was completely destroyed after this, leaving the network down to 7 temperature sensors.

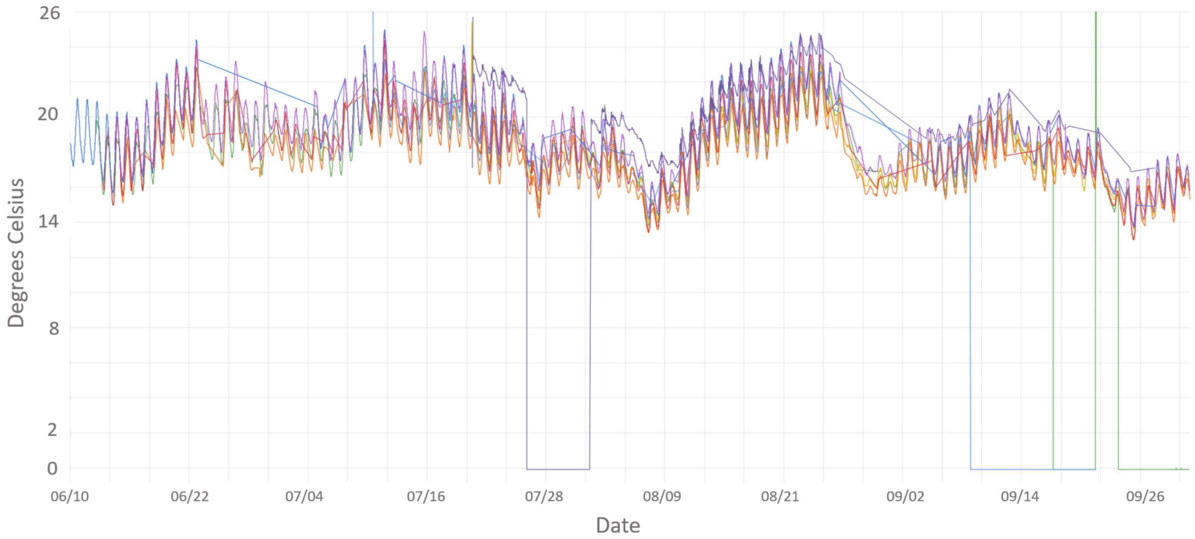

Figure 4.4: *Details of the Grafana dashboards time series display for the totality of the study period.*

Monitoring sensor status and observations are just some of the useful functions of the dashboard - an additional utility is to observe climate patterns. The rapid, sinusoidal wave-like patterns in the data can be attributed to day-night periodicity. Longer term changes however are more interesting to consider. Just after all the sensors were installed at the Kalterbach, Munich experienced a drop in temperature of a few weeks until about the first week of August and this is mirrored in the decreasing temperature at the stream. Things changed however starting around 09-08-2023 when Munich experienced a heatwave. This provided a useful opportunity to explore the influence of extreme temperatures on the water body and data from this period was analyzed in the sections that follow. After this heatwave, the temperatures around Munich returned to a more seasonable conditions and continued to fall as autumn creeped along into the first weeks of October.

4.3.2 Water Height, Discharge, and Flow Velocity

After processing the data from the distance sensor, a basic understanding of the hydraulic cycles at the Kalterbach can begin to be stitched together. The above graph shows the average daily water level from the start of data collection until the end of September. Strikingly, the water level jumps quite substantially in a short window of time towards the end of August. Before this spike, the average water level was about 220 mm. Within a week, the water level jumped nearly 100 mm before falling gradually back down. This period of increase correlates to the end of the two week heatwave which occurred just prior; following this warm period, there was a sudden cold snap which brought with it more rain and damper conditions. Speculatively, this could have been one reason for the sudden increase, however it is also important to note that the Kalterbach is fed by several other smaller tributaries whose water flow are controlled and monitored for agricultural purposes. This spike could have been related to a sudden discharge

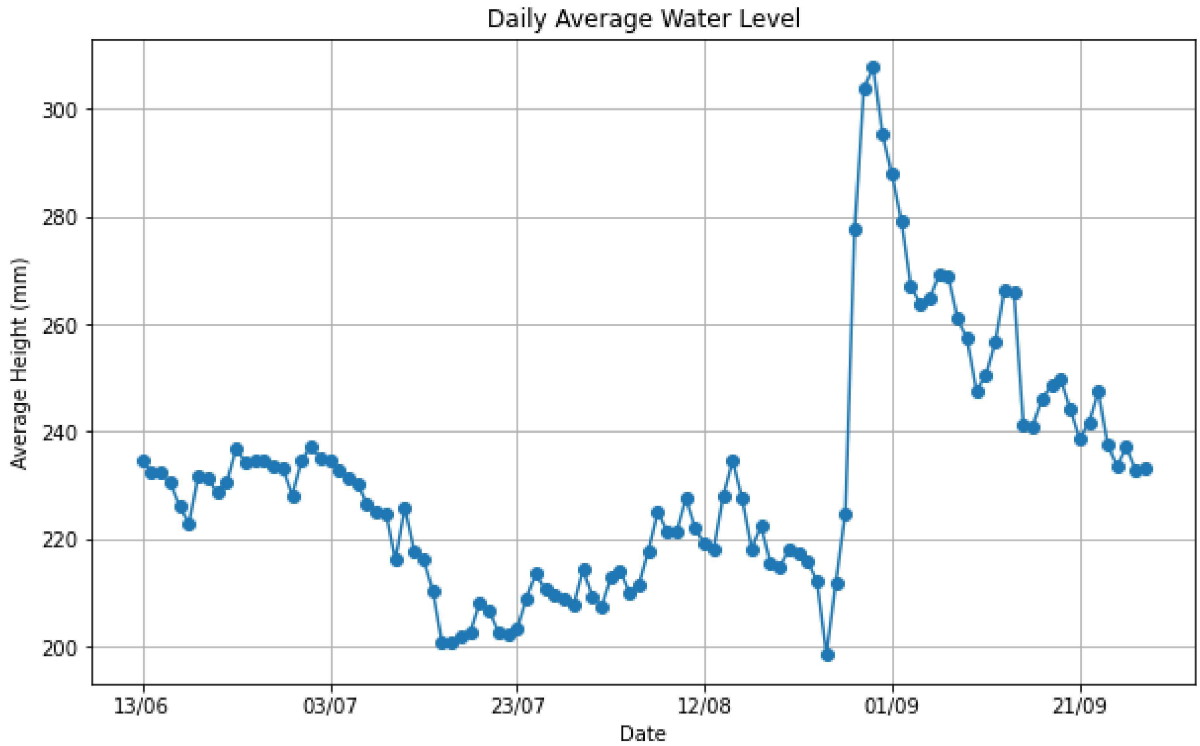

Figure 4.5: *Water level recorded from the distance sensor for the study period*

from one of these water bodies. In addition to this spike, we see potentially some periodicity in about weekly intervals. Water level is a very useful parameter and was used to solve for flow velocity and discharge. Table 4.2 shows the results from these calculations for each month. This demonstrates the capacity for this distance sensor to collect a diverse profile of the hydraulic dynamics at the Kalterbach.

Table 4.2: *Values averaged by month from the distance sensor to understand hydraulic dynamics at the Kalterbach*

Month	**Flow Velocity** $[m/s]$	**Discharge** $[m^{1/3}/s]$
June	0.333	0.401
July	0.319	0.357
August	0.330	0.392
September	0.350	0.461

4.3.3 Daily Mean Temperatures; Individual Points

While the real-time and interactive capacity offered by Grafana proves a major win for the monitoring of the sensor network, it allows only for limited data analysis. To understand trends in water temperature change across time, location, and weather conditions, more sophisticated data mining has to be undertaken. The sheer magnitude of information collected by GSNs allows for many creative manipulations and interpretations of the data; here however, we begin by looking to understand temperature variation for the previously mentioned heat wave which began on 09-08-2023 and broke on 25-08-2023. During this period, all but six days recorded a max temperature above 30 C and days were characterized by high sun and low precipitation. While theoretically any window of time could be analyzed to illustrate the potential of our data, this 17 day heat wave offered the richest opportunity to identify the effect of solar radiation and hot temperatures on the water characteristics at the Kalterbach.

Displayed in figure 4.6 are the average temperatures curves over the course of the entire day for the temperature points on the Kalterbach. The graphs display the real collected data points in blue and display them over a 24 hour period; these were then used to create the red average heating line for the entire two week period. Notably, some sensors have more collected data points than other. The sparseness here is due to unreliable signal connection and can be seen to have a non-trivial influence on the heating curves (take for example the 'south of shadow' which has fewer data points recorded in the mid-morning hours which seems to pull down the average during the hours from 5 to 10). In collecting an average curve of daily temperature variation for each sensor, a picture of heating and cooling within a day becomes clear. All sensors record a day-night periodicity with the lowest temperatures occurring just before or after sunrise at around 7:00. This would make logical sense as the sun has been gone for a maximum period. Conversely, temperatures peak at around 18:00 and begin their decrease through the night. Some areas on the Kalterbach experience more variation in temperature variation. At the river inlet, the periodicity remains fairly stable as it is insulated by the larger Feldmochingersee; On the other extreme, the 'south of shadow' sensor varies the most, fluctuating an average of 6 C between the low and the high. Most sensors however seem to experience a 2 C variation. Notably, the availability of observations varies greatly between sensors and probably contributes to the irregularity of average values.

4.3.4 Daily Mean Temperature Variation; Global Change

In addition to understanding daily trends at individual sensors, it is insightful to relate these nodes to changes in the system as a whole. Figure 4.8 is an interpolation showing the deviation of temperature values along the river from the global mean for three, eight-hour intervals (i.e. morning, day, evening). The actual recorded and averaged temperatures for each sensor is represented by the black dots, while the blue-grey line connecting them are interpolated values. From this graphic we see where - and to what magnitude - heating and cooling along the Kalterbach occur. The total average for the entire Kalterbach during this heatwave is oriented by the grey dashed line at "0". The red dashed line shows the average temperature in the stream for each time condition (morning, day, or night). Compared to the average value for the entire Kalterbach, the average temperature during the morning and daytime values are lower; the former lies nearly one degree below the global average. In a mirrored relationship, the evening hours show an average just over one degree warmer than the total average.

Irrespective of time of day however, for the August heatwave, we see a slight cooling of the stream from its inlet as it runs northward before out-letting at the Amper. We can look at the relationships between sensors to piece together where along the Kalterbach the heating and cooling may be occurring. The beaver dam seems to hold a large amount of heat whose effect is most prominent during the evening hours. From here, as the stream runs northward, it moves through a relatively wooded area before arriving at the 'shadow area' in the forest around Obergrashof. This dense tree cover appears to provide a major cooling effect whose strength depends on the time of day and also tends to increase in the evening hours. Directly after the 'north of shadow' point, the forest thins, sunlight increases on stream, and an increase is once again observed. Notably however, the mixed sun-shade area of the renaturation actually encourages a slight cooling along the Kalterbach.

The pattern of cooling and heating remains consistent across times of day, the magnitude of that change varies notably. Under this lens, the evening deviation varies the most from the other two time periods. Three points of interest are at river inlet, the beaver dam, at the shadow area. Interestingly, although the mean for each time condition increases as the day progresses, the

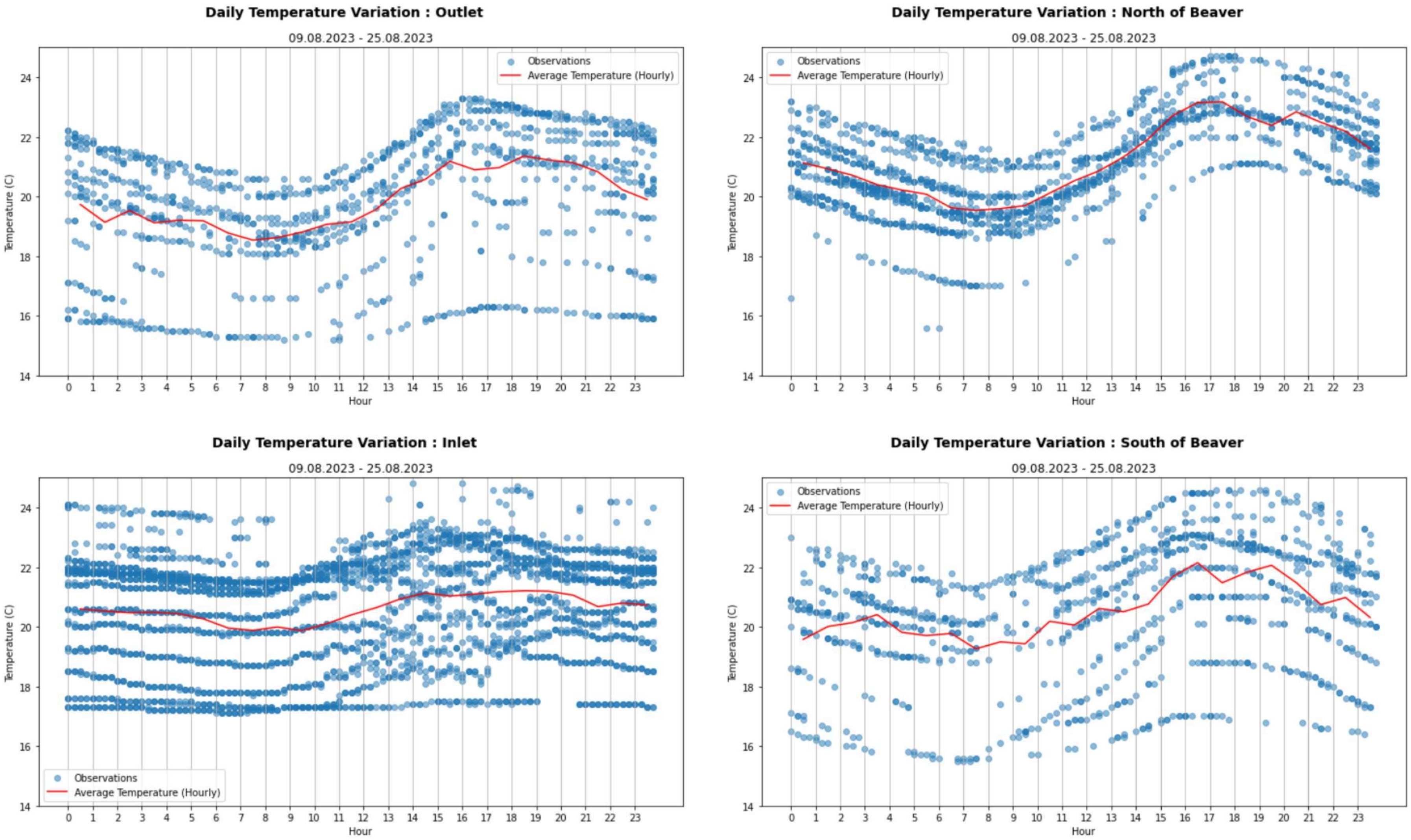

Figure 4.6: *Daily average temperature variations for the inlet, outlet, and beaver dam sensors*

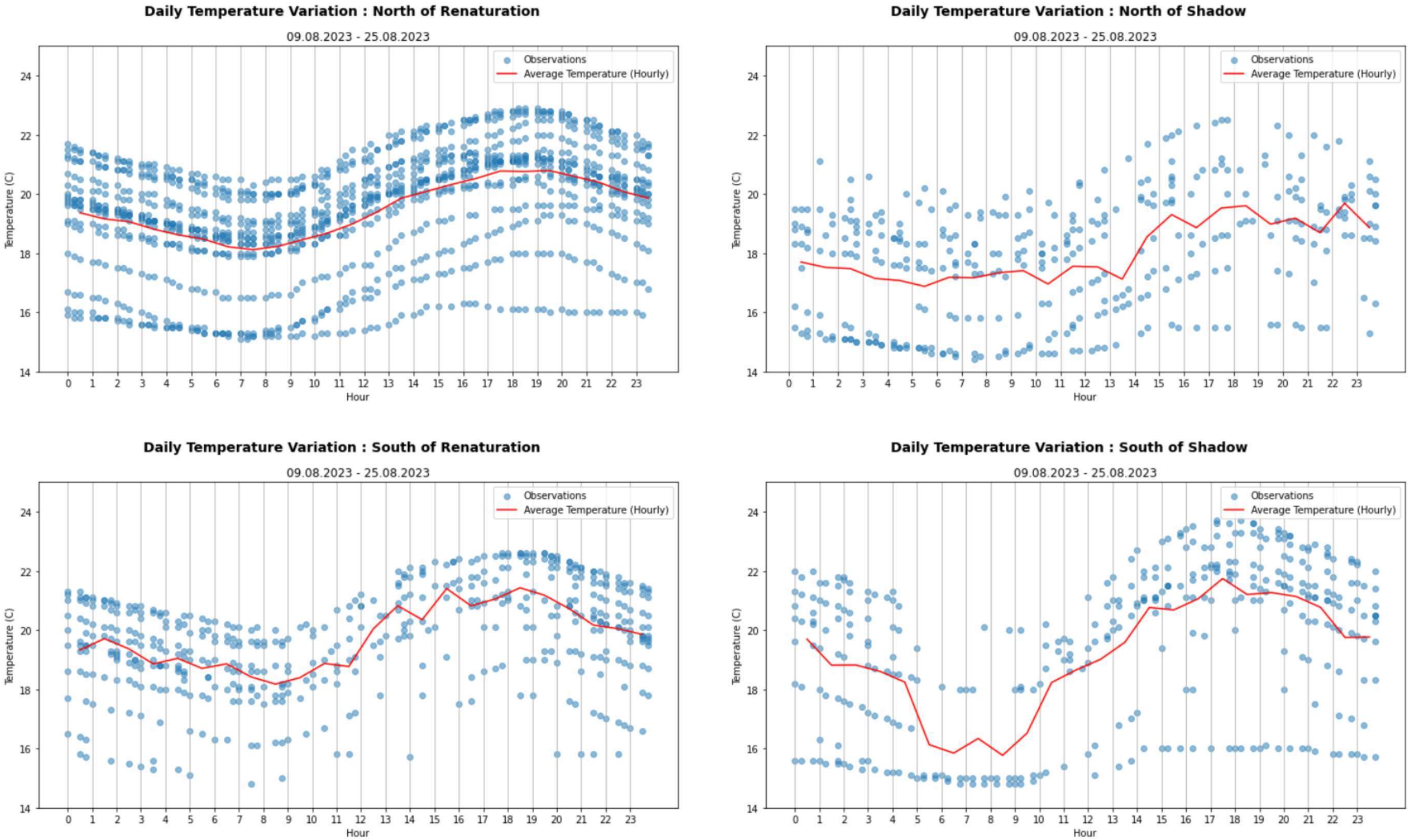

Figure 4.7: *Daily average temperature variations for the renaturation and shadow area sensors*

temperature at the ‘inlet’ does not seem to change very much. The temperature here stays about 1 C above the global average. This is probably due to its location right on the *Feldmochinger See* which would be insulated from large temperature changes due to its size. During the morning and daytime, the beaver dam does have some heating, however in the evening the magnitude of this increase is much greater. The difference across the dam is nearly 1 C, compared to less than 0.5 in the other time conditions. The deep, slow moving water of the beaver dam appears to dissipate heat more slowly than other areas of the stream. The next point moving northward, ‘south of the shadow’, also is notably different than at the other two time conditions. Earlier in the day, this point is well below the mean for the given time period; in the evening, the ‘south of shadow’ temperature is just at the evening average. Interestingly however, the shadow area - characterized by fast moving, shallow water under dense tree cover - still imparts a large cooling effect, in this case nearly 2 C.

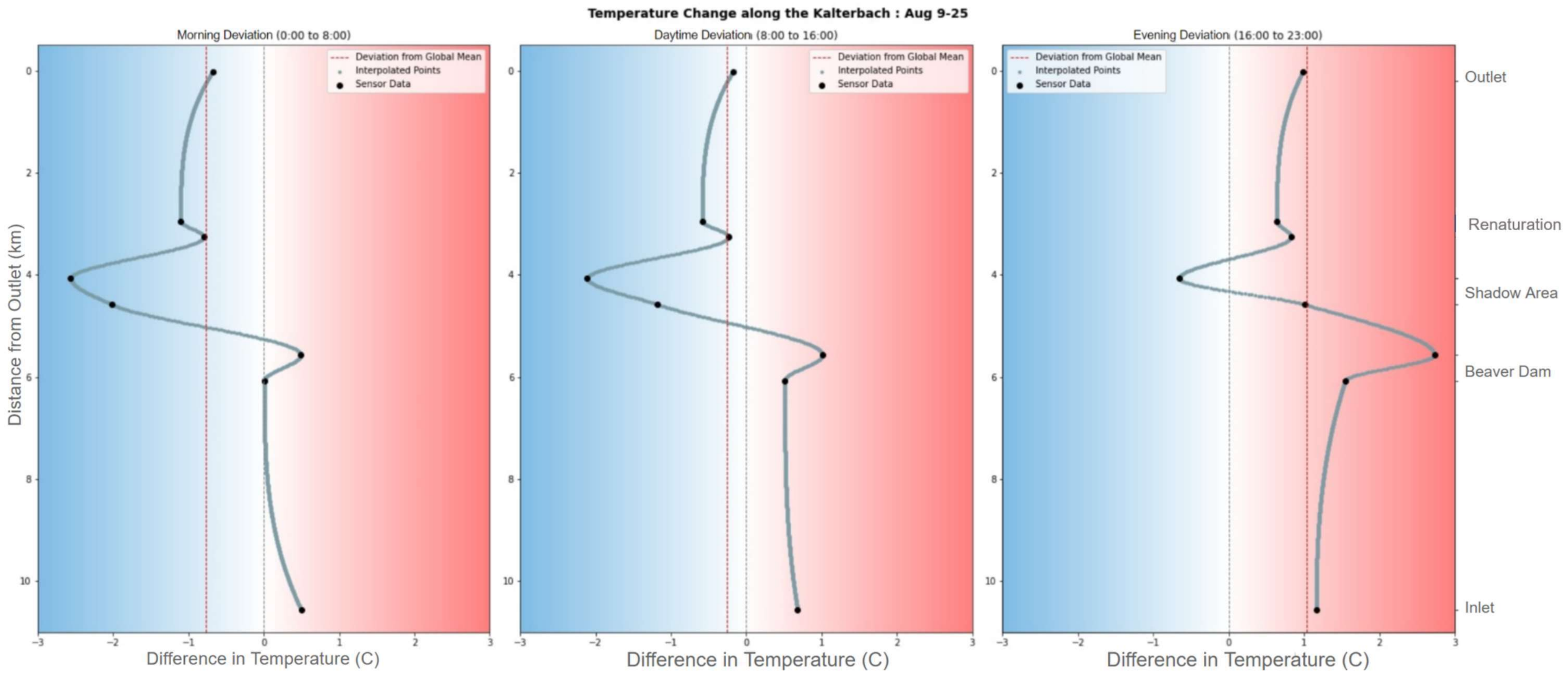

Figure 4.8: *Interpolated deviation from the mean measured temperature across the course of the Kalterbach*

4.3.5 Temperature Variation and Climatic Variables

After looking at the impact of a particularly hot period on water temperatures, the next avenue of investigation focused on the impact of sunshine. Note that the following analysis does not just look at the two week heatwave from above, but instead considers all the data from the summer period. The figures 4.9 and 4.13 show the daily difference upstream and downstream in temperature between four pairs of sensors. The first pair of sensors is between the river inlet and the river outlet, representing the entire average change across the Kalterbach; accompanying this, the three other pairs measure the change across the beaver dam, the shadow area, and the renaturation areas. The left-most, red box-and-whisker plot within each graphic represents all the difference values recorded in the study period - the number of observations represented in this plot can be found under the x-axis labeled n0. The yellow and blue box-and-whisker plots in each graph are subsets of this total observation based on daily sunshine hours. The yellow box-and-whisker accounts only for difference values on days with more than five hours of total sunshine while the blue, right-most plot is for days that had less than five hours of sun.

For the entire Kalterbach, we see that on average, the water at the Kalterbach decreased nearly 1.7 degrees as it moved from the south most point at the river inlet, to the south most point at the outlet. For the beaver dam, the water temperature decreased 0.3 C. For the shadow area, we see 0.6 C decrease, and across the renaturation area we see an increase of 0.25 C. When we observe the subsets of this data based on daily sunshine hours, we observe no significant difference in the temperature change compared to total value in most cases. The only case where we see a significant difference is in inlet-outlet pairing and that is between the “less than five hours of daily sunshine” and both "all values" and the "more than five hours of daily sunshine." Compared to the all values case, subset of temperatures on days with little sun show an additional 0.7 degrees cooling. Its worth remembering however that the low sun subset suffers from notably fewer observations of only n0 = 11 which may artificially skew the data.

A more detailed way of understanding this relationship is to plot the correlation between total sunshine hours and temperature difference across points at the stream. These correlations can be observed in figures 4.11 and 4.12. Here we see that in the case of the entire change of the stream, temperature difference is correlated positively with sunshine hours. As the hours of sunshine per day increase, the temperature does as well; according to the best fit line, the difference from 0 sunshine hour conditions to high sunshine conditions (12 hours or more) is nearly an entire degree increase. The associated correlation coefficient of 0.525 suggests a moderate to strong relationship between these variables for the entire course of the stream.

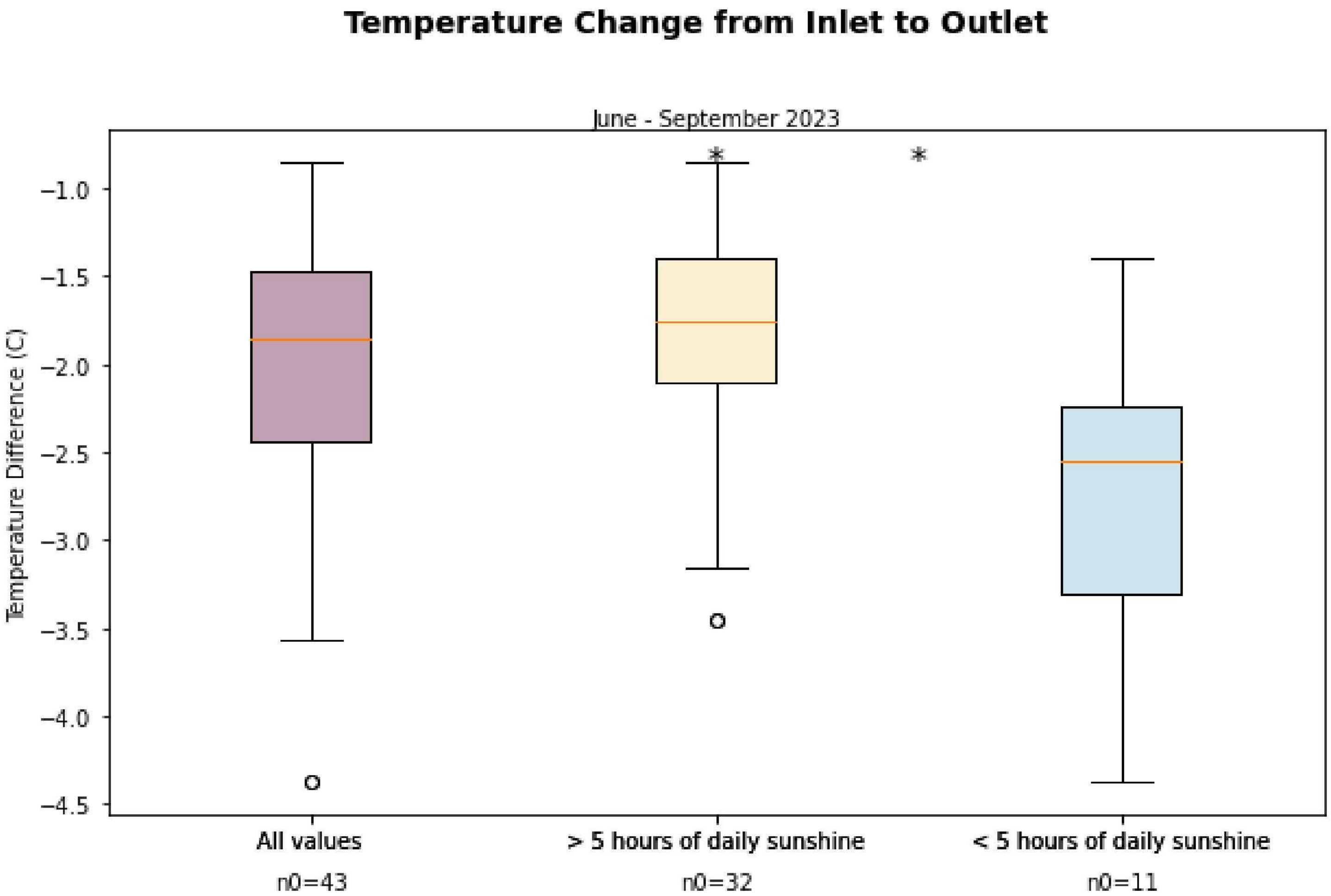

Figure 4.9: *Box-and-Whisker Plot for temperature difference between Inlet and Outlet sensor pairs along the Kalterbach subset by daily sunshine hours for the period of June through September*

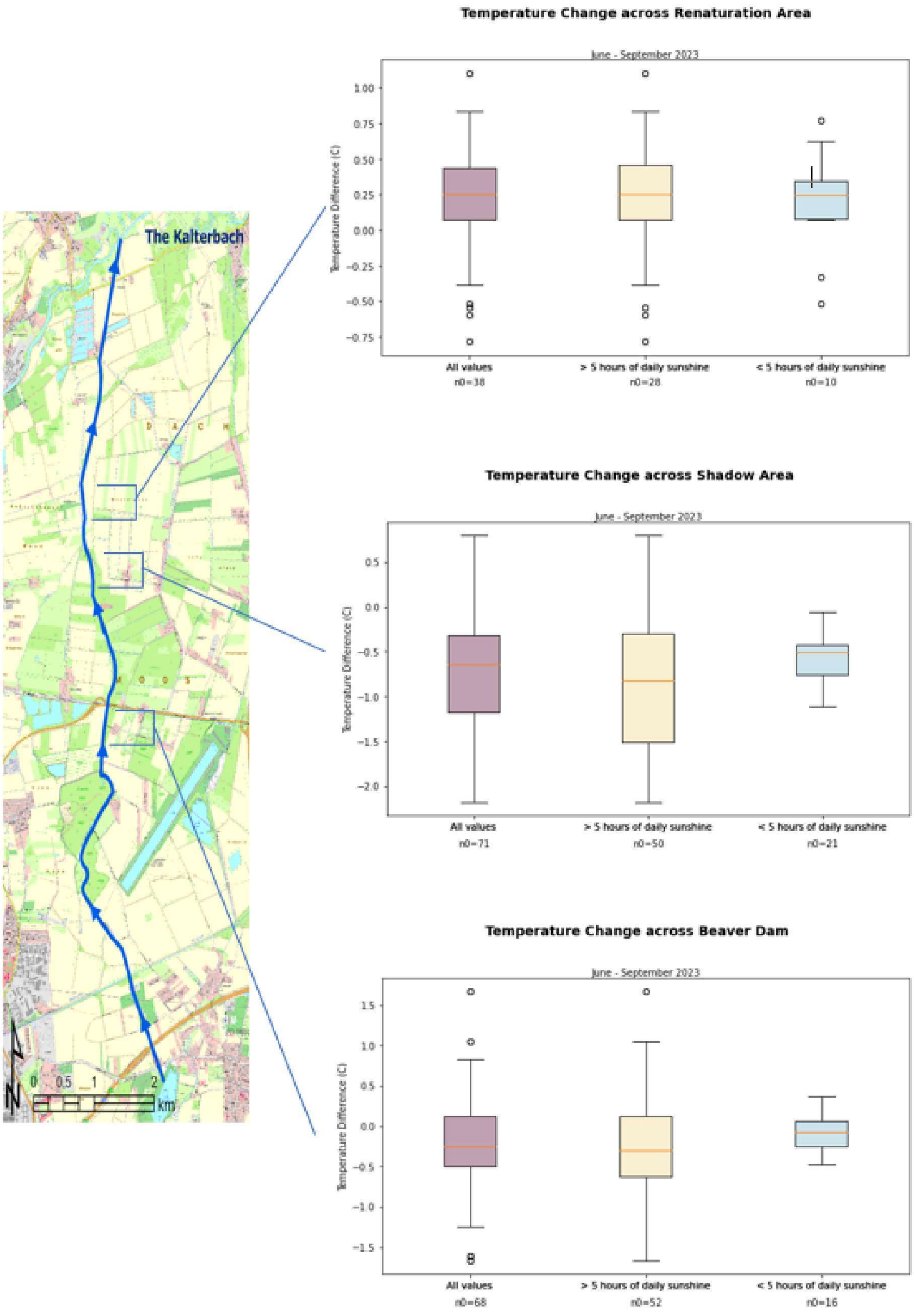

Figure 4.10: *Relationship between sun hours and average daily temperature difference for three landscapes of interest at the Kalterbach from June through September*

For the other sensor pairs, we see a different relationship. For starters, the change across the sensor was much less on average; across the beaver dam this change in degrees was just under zero, for the shadow area it was more at around -0.7, and the renaturation area saw a slight increase of 0.25. These temperature changes seem to pretty nearly match the averages calculated in the previous figure 4.8 for the heatwave period. These are relatively modest changes compared to the inlet-outlet sensor pairing, but makes sense considering the distance being measured; the entire Kalterbach is nearly 11 km long while the other 3 pairings span a distance of about 400 meters.

Table 4.3: *Strength of correlation between change in water temperature and sunshine hours*

Study Area	**Correlation Coefficient**
Inlet to Outlet	0.525
Beaver Dam	-0.072
Shadow Area	-0.234
Renaturation Area	-0.114

A more interesting difference between the inlet-outlet pairing and these three other conditions however, is that the temperature difference between low sun conditions and high sun conditions does not change nearly as much. In other words, there exists no strong positive correlation between sunshine hours and water temperature for any of these three unique landscape features investigated along the Kalterbach. Across all of these features, negative correlations are dominant, however notably, both the shadow area and the beaver dam show some heteroscedasticity which could influence the results. For the beaver dam and the renaturation area the strength of these relationships are extremely weak to the point of being trivial with values of -0.114 and -0.072 respectively. The shaded area exhibits a slightly more robust correlation with its coefficient at -0.234.

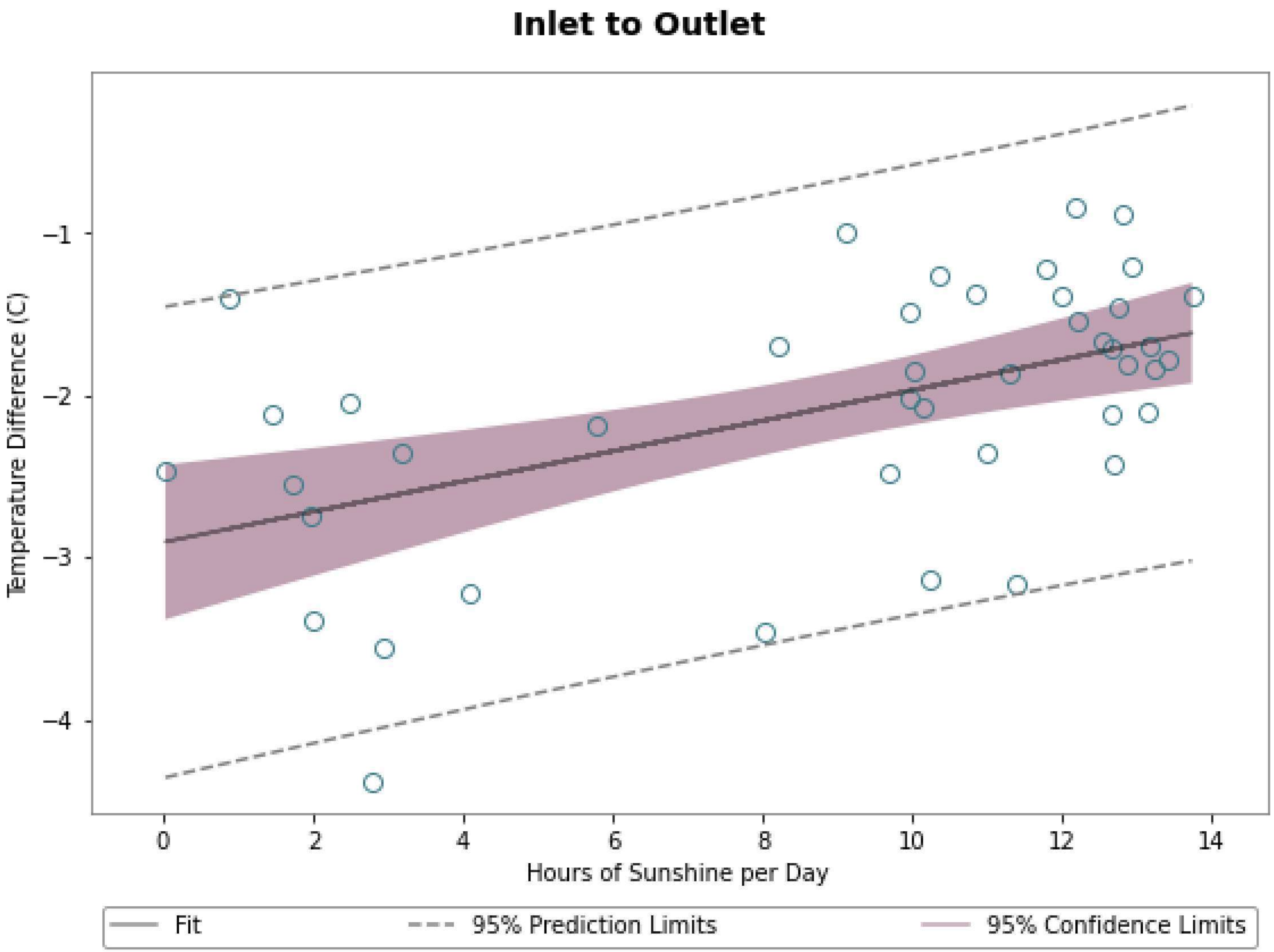

Figure 4.11: *The daily average temperature difference between Inlet and Oulet sensors correlated to the daily sunshine hours for the period of June through end of September*

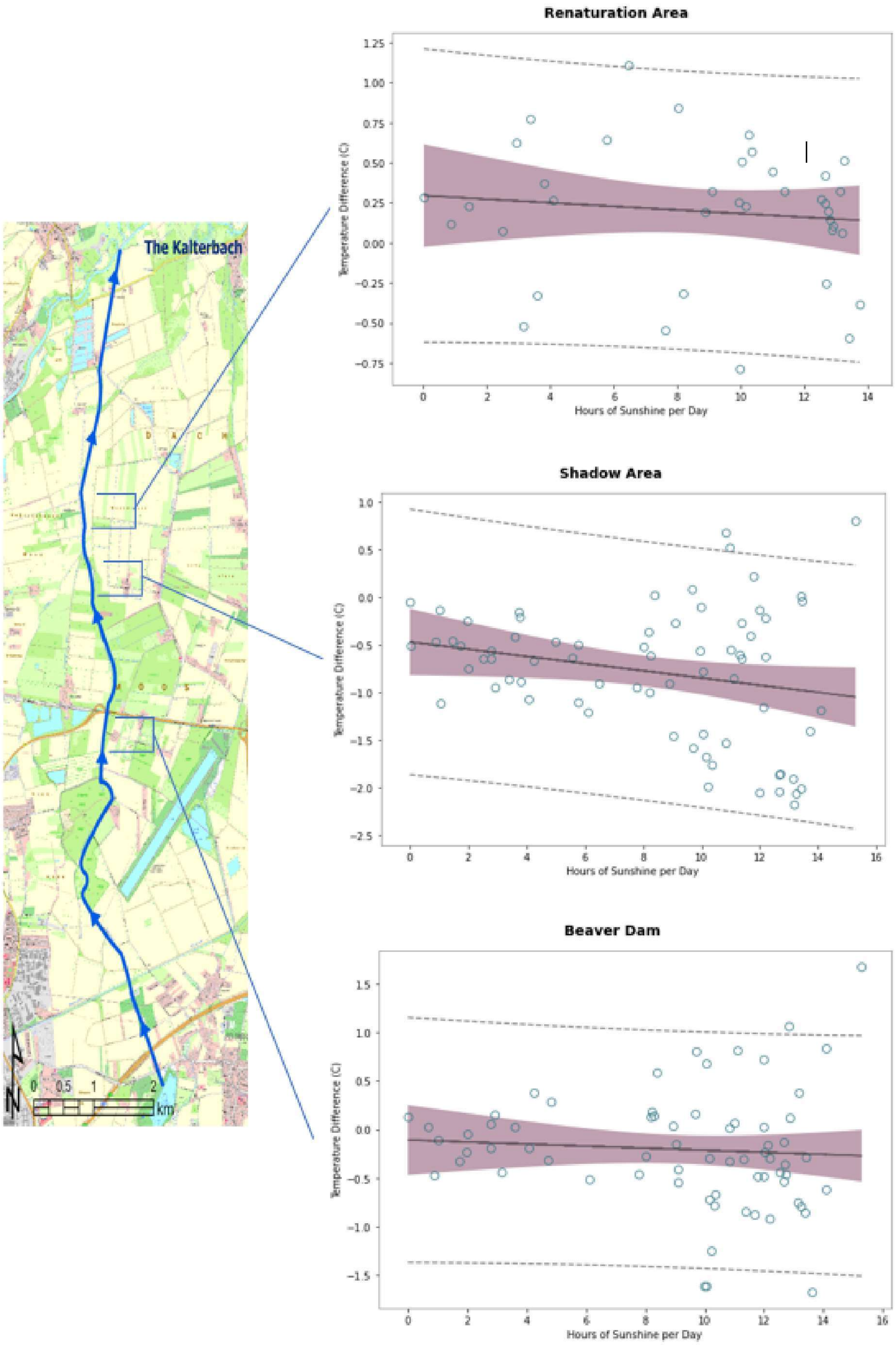

Figure 4.12: *Correlation between sunshine hours and change in water temperature for the other three landscapes of interest*

4.4 Project Assessment

4.4.1 Lessons Learned

Throughout each phase of this thesis, valuable insights were gained, laying the foundation for the potential implementation of similar GSNs in the future. These insights were gleaned through direct feedback from stakeholders who actively participated in the project. Additionally, some lessons were derived from second-hand accounts, summarized from conversations among stakeholders. The results have been documented in the following list, offering a comprehensive overview of the sentiments, challenges, successes, and strategic pivots that characterized the project.

Each lesson learned has been categorized as either a 'win' or an 'issue' for the project as a whole. While it's true that there are more issues than wins in absolute terms, the wins represent significant achievements that underscore the relevance of this data for a wide-ranging audience. The 'recommendations' section, on the other hand, provides valuable insights and suggestions for the future implementation of GSNs and the ongoing development of this technology.

Table 4.4: *Lessons Learned*

Lesson Learned	**Description**	**Win or Issue**	**Exemplary Event**	**Impact**	**Recommendation and Action**	**Success of Action**	**Identified by**
Vandalism	Tampering with the devices may be harder to prevent than expected, attention especially needs to be given to unintentional vandalism	Issue	Children playing at the river took the antenna and threw it into the forest. They were young and could not read the sign attached to the device.	Financial loss (buying another antenna) additional time costs associated with reinstalling the device.	Devices need to be hidden and away from areas of high traffic. Especially good if the devices are high and hard to reach for curious children. Official sign attached to each device with general and contact information.	effective so far	Dawson, June 2023
	Stealing or intentional tampering of the devices seems to be lower than expected	Win	Only one issue of vandalism when more were anticipated and planned for.	More flexibility in where we place the devices. less costs associated with securely fastening the devices.	Unintentional acts of vandalism, primarily by children seems to be a more likely outcome than adult individuals stealing or destroying devices. Rather focus attention with that in mind when setting up the devices.	N/A	Dawson, October 2023

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Table 4.4 – Continued from previous page

Lesson Learned	**Description**	**Win or Issue**	**Exemplary Event**	**Impact**	**Recommendation and Action**	**Success of Action**	**Identified by**
Device Durability	In the open environment, the devices must be durable and might be impacted by changing conditions, especially on a long term basis.	Issue	After a storm, a few trees were blown over. Two devices were impacted. One was only moderately damaged and was reinstalled, the other was irreparably broken.	Financial cost when replacing damaged sensors. Additional long term work of monitoring device function.	Sensors could be outfitted with additional hardware to improve durability. Responsibility for the long term functioning of the devices must be expressed and clarified. Whoever is responsible for the devices must check in on Grafana regularly to identify non-functioning sensors.	N/A	Dawson, August 2023
	Not only humans, but also animals may be interested in the addition of these devices at the river.	Issue	At several sensors, the temperature probe was chewed through. The result was the data stream going from perfectly sending data to suddenly only showing 0 values. The probe was replaced in the field.	Data loss. Additional time costs to modify the sensor with a new probe. Potential financial buren if constantly happening.	A hose was cut out and the sensor probe was strung through it to provide a firm enclosure to protect the rubber sensor probe from animals gnawing on it.	Highly effective protection	Dawson, August 2023

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Table 4.4 – Continued from previous page

Lesson Learned	Description	Win or Issue	Exemplary Event	Impact	Recommendation and Action	Success of Action	Identified by
Signal	Unreliable signal connection.	Issue	Signals for various sensors would cut out for extended periods ranging from a few hours to an entire week. Some sensors in some locations would be more impacted by this than others.	Data loss	Replacement antennas can be bought for around 15 Euro which boost the signal. Locally tweaking the sensor location can increase the signal strength.	After-market antennas greatly increased connectivity	Dawson, Aug 2023
	Potential gateway disconnection	Issue	Multiple sensor can go offline for extended week-long periods and probably indicate a problem with the gateway.	Data loss.	Potential to disrupt the entire project permanently. If one does not want to be reliant on an open source gateway, gateways can be bought for a price of about 600 €, above budget for this project however.	N/A	Dawson, Sept 2023

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Table 4.4 – Continued from previous page

Lesson Description Learned	Win or Issue	Exemplary Event	Impact	Recommendation and Action	Success of Action	Identified by
Dead zones at various locations on the Kaltenbach	Issue	Some areas of the Kalterbach had little to no signal as they were not near enough a gateway, or the local topography blocked the signal	Inability to collect data at various points. Modification to the original network plan.	Repositioning the devices can make a difference (i.e. installing at a less forested area, attaching the sensors as high as possible) Testing the signal beforehand with a test device can provide an idea of feasibility before deciding on sensor locations for the network.	Repositioning can help optimize signal, but it may remain weak	Dawson, Aug 2023

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Table 4.4 – Continued from previous page

Lesson Learned	Description	Win or Issue	Exemplary Event	Impact	Recommendation and Action	Success of Action	Identified by
	Gateways are open source	Win/ Issue	Because LoWARAN gateways are open source, a network can be established by collective action. This allows a network to arise without planning from a central authority and diminishes the cost to entrance. However, although unlikely, the problem remains that gateways can just as easily be taken down and signal for an entire area can be lost.	Insecurity for the long term functioning of the project. Potentially high cost investments to buy a gateway later on. Open source model decreases initial cost (win)	May need to invest later on for a gateway that would allow the continued functioning of the project independently	N/A	Dawson, Aug 2023
Data Quality	Data has high level of resolution and accuracy	Win	The sensors are able to (qualitatively) resolve the signal accurately and don't suffer from much noise. The water height sensor measures in sub cm range and the temperature sensors can record data even in extreme negative degrees.	Increased relevance of the GSN at the Kalterbach as a model project. Potential for future projects and paradigm shifts in how renaturations are undertaken.	This high quality data could even be considered greater than the needs of the project, but allow for fine level, highly accurate conclusions to be drawn from the project.	N/A	Markus (Terrabiota), September 2023

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Table 4.4 – Continued from previous page

Lesson Learned	Description	Win or Issue	Exemplary Event	Impact	Recommendation and Action	Success of Action	Identified by
Data Processing	Data is easily accessible, interpretable, and offers a variety of levels of analysis	Win	Data can be easily downloaded and accessed for processing. It seems to have utility for both simple statistical analysis as well as more high-level modeling. Processing in python was straightforward and productive.	High impact results even without intensive computational analysis. Shear size of the data has high potential for future, more involved analysis.	In future, more time should be invested in data analytics to extract a deeper understanding of the hydraulic processes occurring at the Kalterbach (ex. Time series and trend analysis)	N/A	Dawson, August 2023

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Table 4.4 – Continued from previous page

Lesson Description Learned	Win or Issue	Exemplary Event	Impact	Recommendation and Action	Success of Action	Identified by
Some data visualizations and databases require deep technical expertise in order to prepare relevant results	Issue	Although initially very straightforward, data manipulation on Grafana quickly became unintuitive and complex. To extract more sophisticated results from the data in applications like python, a high level of technical competency in several fields (hydrology, coding, etc.) is required. While this represents a certain opportunity, it also suggests decision makers must externalize analysis to consultants or data scientists - for poorly funded environmental agencies, this could be outside of their resources.	Unsustainable for long term, internal functionality of the project. Necessitates continued investment with technical expertise like the TUM. Not necessarily ideal.	Additional academic partnership could be established with the TUM and other stakeholders such that future masters thesis volunteer their time to help the project. Stakeholders with more resources such as the WWA or Terrabiota could manage some of the more technical aspects.	N/A	Dawson, August 2023

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Table 4.4 – Continued from previous page

Lesson Learned	Description	Win or Issue	Exemplary Event	Impact	Recommendation and Action	Success of Action	Identified by
Management	Sensors require a fair deal of maintenance, often due to hardware. This means visiting the sensors in remote areas to carry out a repair which is not ideal for environmental monitoring.	Issue	Sensor often go offline - sometimes this happens as a result of damage to the device, while other times this is just a temporary disconnect from the signal. It can be difficult or impossible to tell the reason for a sensor no longer sending; when the problem persists, physically checking the sensor in the field is required.	The sensor network needs to have an individual responsible for its maintenance. Relative to alternative data collection methods, the additional work of a IoT network is low, however it is still non-zero.	A physically present individual must be clearly appointed to take over and monitor the network. The technology is not yet at a position where we can expect to let it run without any maintenance for the whole life span of the battery. Investing in higher durability sensors could decrease revisits for repair.	N/A	Dawson, Sept 2023
Scope and impact	Project is scalable and broadly applicable	Win	The project garnered attention from additional administrative entities such as the WWA and its relevance was deemed potentially greater than just for the Kalterbach	Increased relevance of the GSN at the Kalterbach as a model project. Potential for future projects and paradigm shifts in how renaturations are undertaken.	Continuing to invest in the project would seem to benefit the renaturation and those involved. Additionally, advertising the success of the initiative to other similar programs would be broadly beneficial.	N/A	Dawson, August 2023

4.4.2 SWOT Analysis

Figure 4.13: *A SWOT analysis compiled in consideration with the Lessons Learned*

The many Lessons Learned were crystallized into the above SWOT analysis. The green section represents the strengths (S), the orange section the weaknesses (W), the blue section is the opportunities (O), and the threats (T) are in purple. Broadly, the GSN at the Kalterbach proved to be highly useful for environmental decision making, especially when considered against the alternative methods for collecting this data at scale and quality. The data was regularly praised as lending an important contribution to the renaturation efforts by various stakeholders. The data demonstrated the impact of various landscape features in warming or cooling the Kalterbach. This wealth of data was collected on a budget previously unimaginable before the development of these IoT technologies.

Challenges and limitations around the network concentrate primarily on hardware - two sensors were lost over the course of the summer due to hardware malfunctions and several others had to be visited to care out repairs. On top of this the signal strengths were often weak and could cut out for long periods, decreasing the quality of the data. Finally, the network depends on an externally run gateway and if the owner of this gateway take it offline, the entire network could cease to function. Assumedly these hurdles can be over come with a bit more investment in sensor hardware or the purchase of a gateway, this however is not always a possibility for cash strapped environmentally focused organizations - one does not go into environmental protection if they are looking to make the big bucks.

Other threats identified here extend beyond the specific case of the Kalterbach and deal with broader GSN uptake. At the Kalterbach, open source softwares and standards were primarily used to establish the network; this meant cost could be minimized, bringing them to the financial realm of possibility for a publicly funded restoration project, however it also meant that more technical work fell directly on the shoulders of those establishing the network. In this case, the technical work was externalized to a university, but without this support, it appears the installation would be too complex to be established by nonspecialists. This could threaten the ability for other environmental organizations to incorporate IoT into their work process. Importantly, one should keep in mind that the Kalterbachs GSN is probably operating at an extreme end of the financial spectrum with results being delivered on a very slim budget - with a bit more resources, many of the issues here could seemingly be overcome.

5 Discussion

5.1 General Successes and Limitations

Held against the research objectives discussed in 1.3 of this thesis, the installation of the GSN at the Kalterbach can be considered a success. The primary research objective to "implement a geosensor network in an open nature setting at the Kalterbach and to assess its success, the utility of its data for informed environmental decision making, and the potential barriers to future uptake of this technology in similar use cases" was broadly achieved. Although the network experienced some issues which prevented its fully actualization as compared to the original aspiration, a substantial network of nine sensors were able to be connected and successfully send high quality data on water temperature for several months. Postprocessing and analysis of this data resulted in valuable insights into the nature of heating and cooling at the stream and stakeholder interviews confirm that this data helpfully informs the direction of the Kalterbachs renaturation. The entire project can be used to model future implementations of IoT in the open nature setting; the relatively limited documentation of application cases for remote environmental monitoring mean the lessons learned here can help to structure future projects and make GSN more broadly accessible technology.

Because the renaturation of the Kalterbach is still in its early stages, the degree to which this data will truly inform decision making has yet to be seen, however, if we consider the counterfactual without this GSN, it's utility becomes clear. Without the installation of this GSN, no alternative form of data collection seems to exist which could match the capabilities of this IoT technology. A sub-objective of the thesis aims to "analyze and present the data in a way that provides useful insights otherwise unattainable for decision making in the renaturation of the stream." The wording "otherwise unattainable" highlights a major strength of the technology - it really seems impossible to collect this data in any other way. Using traditional means, even with a massive budget (uncharacteristic for anything ecology related), no amount of money could immediately and consistently deliver you the water temperature of a stream in the middle of the forest at anytime of day or night. This finding reemphasizes those found in the paper by Ascui, Haward, and Lovell [9] speaking on the success of the aforementioned harbor monitoring program in Section 1.3 which allowed for more data to be recorded in a single day than the entire pre-IoT monitoring program. Despite the remaining technical shortcomings of the technology, no alternative can compare to IoT's capabilities in the field of environmental monitoring.

Various stakeholders at the Kalterbach deeply appreciate this data and have expressed its utility in the renaturation project and beyond. Even before the analysis here was available, stakeholders have brought this data forward in its more raw form and used it in meetings to structure arguments around effective stewardship of the water resource. Additionally, the WWA has expressed they would be interested in the technology for future monitoring schemes depending on the final outcomes of this project. The generated excitement and real impression it has spurred in those responsible for managing the Kalterbach speak volumes to the GSN's importance and impact. Although time will tell how deeply this data will steer the restoration, the resolve seems to be that this data is productive, worthwhile, and useful.

Another success highlighted by the GSN at the Kalterbach lies in the affordability of the technology to deliver results. This network was installed by a single individual at a price under 700 €and all results were compiled in under a six month period. Even despite relatively shallow pockets and minimal resources, several compelling conclusions could be drawn from the collected data. An important factor for this affordability is the free, standard and open-source technologies which back much of the this work. Without the openly accessible data infrastructures like the TTN or the OGC SensorThings API standard among others, this technology could not effectively deliver results. This positive impact argues for the continued move towards open standards and access. Many of the shortcomings of the project could feasibly be mitigated with slightly more investment into hardware. Taken as a model project demonstrating an open-nature use case, this thesis seems to suggest that IoT has a place at even hobby-level environmental monitoring schemes. This democratizing potential of IoT is a major takeaway from the thesis which has important implications for how we understand the environment.

Beyond just the hardware and data infrastructure being affordable, high quality analysis of this data also does not need to equal intense time and financial resources. Shifting norms which recognize the importance of open-access data has meant that a wealth of additional, complimentary data can be downloaded for free online. Fusion of IoT data with other complimentary data sets collected by other actors enhances analysis. Emergently complex conclusions can be drawn from this synthesis of data. As previously mentioned, this thesis took from the *Deutsche Wetterdienst* and, even without intense manipulation or complex algorithms, was able to draw conclusions about the nature of heating at the Kalterbach in relation to sunshine hours. These relatively rudimentary conclusions could readily be amended with more complex analytical techniques like machine learning or to account for additional data such as ambient temperature, topography, hydrology, fine-point elevation or other supplementary in situ data sets.

As with any good project however, the installation of the GSN is not without its limitations. While more general suggestions and persistent limitations of GSNs will be discussed in the following sections, the limitations referred to here are specific to the context of the Kalterbach and highlight lapses in the study protocol and which should be improved upon in the future. Although just identified as a success, the budget provided for the Kalterbach can also be seen as an shortcoming. The shoestring management of this GSN showcased the cost-effectiveness of data collection, but it occasionally felt somewhat DIY and close to being unsustainable. With a bit more financial support and extended resources, the project could have been much more reliably successful. A higher budget would have allowed for the replacing of the "south of renaturation" sensor for example when it was damaged in the storm. The cost-to-reward ratio of having all the sensors up and running as planned should be quite low, but there was not room in the budget to allow for that addition. A similar example comes to mind in buying of additional antennas; for a marginal additional cost, higher strength antennas could have brought on line several other sensors, improving the quality and scope of the data analysis substantially. Not just in financial resource, but also material ones, the ability to use a car - rather than just a bike - to get to the sensors, would have greatly increased the efficiency of the project. Resources were just stretched slightly too thin for comfort for the installation of the GSN as a whole.

On a tangential topic, an additional limitation which potentially influenced the quality of this thesis project, is the very interdisciplinary nature of the work. As a general rule, I would argue that in order to actualize the benefits of our many wonderful scientific developments we must move in a more interdisciplinary direction; this is especially true of topics in climate change which touch nearly every corner of society and require multifaceted thinking to overcome. In this way, the holistic nature of this thesis represents a strength, however, it also inherently means that some sections could lack depth. This project simultaneously requires at least some knowledge in data science, hydrology, ecology, environmental politics, land management, electrical and environmental engineering, and, of course, geoinformatics. This wide spectrum of knowledge leads to certain limitations in conducting comprehensive and in-depth analysis around certain aspects of the GSN. This limitation becomes particularly evident when examining the intricate dynamics of heating and cooling in the Kalterbach, as discussed in sections 4.3.4 and 4.3.5. A notable difference in results between these two analysis is the impact of the renaturation area on heating. In 4.3.4, this landscape feature cools the stream, while in 4.3.5 it heats the stream. Upon more closely evaluating the data, this discrepancy seems to be due to lapses in data collection by the sensor to the south of the renaturation area. While some data cleaning was done to allow for comparison between the sensors (i.e. removal of data points with insufficient collected data, see section 3.4.2 and 3.4.3), this is a fairly rudimentary way of preparing the data for analysis. To make sensors more comparable between one another, the most optimal solution would be to run a modeling program (for example, Auto-regression Moving Average (ARMA)) to the time series and fill in the gaps [44]. However, while this is theoretically possible, the requirements to carry out this analysis this were beyond the skill sets of the author and exceeded the time demand of the thesis.

In a real world implementation of the GSN, preferably tasks should be distributed to more specialized individuals thereby maximizing the return on investment for the network and domain experts will use the raw data for further analysis. More careful preparation of the time series data could improve the quality of the results and avoid disagreeing conclusions such as in the above case. With a deeper understanding of hydrology as well as the more sophisticated tool for data mining, one can imagine complex relationships could be extracted from the combination of temperature and water level data. Because this thesis intends to acts as a demonstration of the potential of GSN in this use case, the hesitation to go too deep into a single direction can be forgive - the multitude of diverse skills are just a bit too much for one person to manage alone. In the future utilization of IoT however, one hopes that diverse thinkers can be brought together to capitalize on the promise of the technology.

5.2 Persistent Challenges and Accompanying Recommendations

While the project can largely be considered a success in the context of its stated objectives, there remain several challenges that could impact future reproductions and prevent the larger scale adoption of this technology. Some of these challenges have already been identified across IoT and GSN literature while others are more tailored to this use case. The ‘Lessons Learned’ in Table 4.2 represent crucial results of the thesis; from this careful documentation of wins and challenges in our GSN, we hope to cue research to continuing areas of development in IoT and alert future IoT applications to issues for deeper consideration.

5.2.1 Hardware Durability

The most immediate challenge facing IoT and GSN in open-nature environmental monitoring concerns hardware. Time and time again, delays in installation and repeated maintenance came down to insufficient hardware given the conditions at the Kalterbach. At the beginning of the project, it took nearly three times as long as expected to install all the sensors at the Kalterbach. Finding an appropriate installation site involved a compromise between several factors; these included: (a) matching the locations previously identified by the stakeholders, (b) being hidden in a secure location safe from tampering by the public or curious animals, (c) connecting to the network with a strong, reliable signal. Fulfilling all these wishes was not always possible given the available hardware. In some cases, a desired installation site was in a signal dead-zone and the sensors antennas could not connect to any available gateway. In other cases, establishing a strong signal would mean placing the sensor in an overly obvious location where it would receive a lot of unwanted attention. Even if the sensors could be installed in an appropriate site with a strong signal, this did not guarantee that sensor would be able to record data for a long period. The harsh, unpredictable conditions of the outdoors meant the sensors were completely subject to the elements. Only three months after installation, three different sensors experienced some type of hardware malfunction. This fact highlights the reality that, given the current hardware at this price point, GSN will not be up to the task of recording environmental data in the open-nature setting long term and automatically unless this issue is addressed.

Some aspects of addressing this hardware challenge will necessarily be unique to each open-nature case - the hardware challenges will not be the same when recording in the desert cerise the jungle cerise the ocean. An important step to incorporate into each new development of a GSN should be to think deeply of potential hardware issues unique to the environment you are trying to monitor. DIY additions to the network, such as the protective covering of the hose around the water temperature probes in this thesis, can help the GSN to function more smoothly and for a longer uninterrupted period. Additional, more sophisticated enclosures could be fitted to the sensors as a means of shielding them from the elements. Retrospectively, this thesis should have focused more time and energy in the early planning stages on the hardware limitations and potential hardware improvements. In doing this, time could have been saved in both repairing and insulating the network. A general recommendation for all potential, open-nature GSNs would be to concentrate more on this aspect of the network before even beginning with installation. In the most optimal case, this could even involve a trial phase where one sensor is installed in an exemplary setting and hardware lapses are identified before installing all the devices. This could save money and improve outcomes.

5.2.2 Maintenance and Technical Accessibility

While improving hardware should greatly decrease the vulnerability of GSNs, the reality remains that in remote, open-nature settings, unexpected disruptions will occur. Even in the highly funded river monitoring system by Adu-Manu, Katsriku, Abdulai, and Engmann [3] who used quality sensors on a large budget, damages occurred to this system which could not have reasonably been prevented against (in this case, alligators bit through the water monitoring probes). In more highly funded projects, repair is not a cause for much concern because such projects typically involve highly skilled and knowledgeable individuals who would tend to the software and hardware issues. However, as outlined in section 2.4, a key implication of IoT technologies in environmental monitoring is the ways that it changes the modalities and agencies of environmental governance to include more diverse actors and increase data transparency. We would hope to expand environmental data to be in the hands of immediate stewards of the land; while these individuals would have some of the deepest knowledge of a local ecology and could contextualize this sort of environmental data most readily, they may not have the technical knowledge to upkeep or install an IoT network. This was observed at the Kalterbach especially in considering how to transfer the network from the purposes of this thesis to the stakeholders. While the technical know-how required to maintain a network is significantly less than that necessary to install one, there remains a level of technical understanding needed to repair malfunctions and hardware damages. For the specific example at the Kalterbach, the responsible party does have some electrical education and can repair a broken sensor probe if need be, but anything more would likely not be solvable. This makes the extreme long term viability of the GSN at the Kalterbach unfortunately doubtful. Therefore, considering the broader generalizability of GSNs for use in more local, municipal, or non-governmental applications, the current outlook requires a certain level of education before the technology can be widely adopted.

In addition to the skills training likely required by individuals looking to utilize GSN, additional developments in the IoT workflow could potentially precipitate ease of use for environmental monitoring. The SensorThings API data standards established by the OGC has helped to encourage uptake of IoT by easing its interoperability among other improvements [33, 42].

Additional standards could be taken up which further streamline the use of IoT - especially with regards to bringing the devices online. This process involved working with several softwares in tandem; entities had to be registered in the TTN, then they needed to be created in the FROST data server, then these had to be mapped together using MongoDB, payload conversations were applied with Cayanne LPP, and complex queries had to be formulated in Grafana to display it. Within this workflow, there seems to be potential for streamlining the process by linking these softwares together. Especially as AI improves, it is reasonable to assume that this workflow could be automated with the machine prompting for necessary information unique to the network. Even just this shift from code to natural language could increase accessibility of IoT by requiring little to no software knowledge to set up a network. In order to further democratize IoT and bring about improved land governance as a result of expanded agencies and transparencies, additional focus should be directed toward how to synthesize the steps to configure a network.

5.3 Implications for Renaturation of the Kalterbach

While there is a certain joy in the pure pursuit of scientific discovery - science for science sake - I firmly believe that alongside this purely epistemic endeavor, there is a responsibility to demonstrate that these efforts indeed have a positive influence on the world A major goal of this thesis work is not just to understand *if* a GSN can successfully be installed for open-nature environmental monitoring, it also embarks to determine *how* - if at all - it can influence our understanding of natural systems and the ways we plan their use and function. As the title of this masters thesis states, the hope for this sensor network is that it can be effectively harnessed for environmental decision making. Putting ourselves then in the place of these environmental decision makers, how would we learn from and what would we do with the data and analysis coming from this GSN? Does the data collected here inform us on how we should continue with ecological restoration of the Kalterbach? By interpreting the data from the perspective of these end users and showing its relevance to land stewardship, we can build a compelling case for the continued implementation of GSN in this context. To achieve this, we will examine the data in the context of the original research question that initiated the GSN project at the Kalterbach: Does the ongoing renaturation of the Kalterbach, including the addition of more dragonfly windows to support the endangered Helm-Arzurjungfrau, potentially endanger fish species by elevating solar radiation on the stream and, consequently, significantly raising water temperatures?

In the most coarse reading of the data, we are immediately proven that different landscapes impart varying changes to the streams water temperature. In figure 4.8 we observed how these changes are not uniform across the length of the stream or during various times of day. This would give data-driven merit to the logical argument that the landscape can be wielded as a tool to modify water temperature. Under the extreme high temperatures plotted in figure 4.8 for example, the data would suggest the addition of beaver dams would continue to raise temperatures, however more shaded, forested areas and renaturation areas could decrease them[1]. While interesting enough - especially when investigating how more renaturation sites could impact things - this provides only scant insight that can be transferred for the question posed above.

The analysis of the sunshine hours and water temperature however deepen own understanding

[1] Notably however, this cooling impact of the renaturation areas is probably a result of lapses in data collected by the south of renaturation sensor. For this two week heatwave period, besides this device all the other sensors maintained reliable signal and data can reasonably be trusted as showing the cooling or heating dynamics of the stream. For the real impact of the renaturation area, the analysis from Section 4.3.5 which looks at the temperature changes on the Kalterbach for the entire summer, provides a more robust picture of temperature dynamics. This is because this analysis has many more observations, therefore increasing its power. Lapse or outliers in the data do not have such a dramatic impact on the results as compared to only a two week period.

of how we can apply the data to determine what future renaturations should look like. Looking at the correlation analysis in figure 4.13 we see that, at least in the global context of the water body, sunshine does play a role in temperature. From the Kalterbach inlet to its outlet, the stream cools by an average of around 2.4 degrees during summer conditions. However, when there is no sun beating down on the water, the cooling is large (about 3 degrees), while when the whole day is sunny, the temperature decrease is smaller (just under 2 degrees difference). Why does this decrease in cooling happen? Are open, exposed areas along the Kalterbach mediating this change? Looking at the beaver dam, the shadow area, and the renaturation area, it does not seem sunshine decreases the cooling potential or increase the heating potential of these landscape features. Instead, there must be another point on the Kalterbach that is responsible for the decreased cooling on sunny days. Potentially the "full sun" area which unfortunately was not able to be connected to the GSN, could be more impacted by sunny days than the other areas.

Specifically interesting in this regard is that sun exposure at the renaturation does not increase heating in a measurable way. This goes against what one might expect as this stretch of the river is quite exposed with about half sun and half shade. While we do see a temperature increase of nearly a quarter degree Celsius across the course of the renaturation area, there is no correlation between those temperatures and sunshine. With this in mind, while although the addition of new renaturation areas might push the temperatures up, the mechanism driving this heating is likely not due to solar radiation on the river as a result of clearing trees for the rewilding. Something else is, at the very least, more responsible for driving that change: the slower flow velocity of the winding renaturation area could cause a gradual warming of the water as it flows northward; the ambient temperature could have a much more significant impact on heating of the water than sunshine; the ground water contribution at this section of the stream might impart less of a cooling effect.

So how does this all help the environmental decision maker who wants to support our friend the Helm-Azurjungfern? Immediately, we are made aware the complexity of the system dynamics at the Kalterbach; the base argument that including more dragonfly windows would drive up temperatures because of increased solar radiation probably is - at least based on this limited data analysis - not so simple. While sunshine hours do correlate to decreased cooling across the entire course of the stream, the landscape feature of a dragon fly window, probably would not contribute too much to heating. This claim comes from the fact that dragonfly windows (small pool on the side of the river with limited tree cover) are physically most similar to the renaturation area, but even smaller in scale. The data revealed no correlation at the renaturation, so therefore it would be illogical to assume one would be found at a dragonfly window. However, while - when taken in isolation - the data seems to indicate that sunshine is not the driving factor influencing heating for this landscape type, it importantly does not support the claim that has no influence. Rather, it encourages that we shift our attention from solar radiation as the primary concern for future renaturation efforts to consider a more nuanced, myriad set of factors.

It is here that the data analyzed for the purposes of this thesis begin to reach their useful limit, however it does not imply that the data as a whole have been milked for all it's worth. Many more insights contend to be extracted from the GSN's data. The next steps would be to incorporate additional data sources into the analysis and control for the variables that were not considered in this preliminary round. Ambient temperature or humidity can be publicly accessed to determine the interplay of all these climatic variables on the water temperature. hydraulic modeling was unfortunately beyond the scope of this thesis, but by making use of digital terrain models and the water level data collected by our sensors, a finer picture could be pieced together of heating and cooling dynamics. Importantly, as discussed above, incorporating more sophisticated time series analysis techniques such as time series modeling would prove useful in order to compare more full time series against data from other sensors. Flow velocity and discharge of the stream were calculated using data from the height sensor. Although this thesis did not have the time or academic means to take that analysis further, conversations with environmental engineering stakeholders substantiate that this information could later be linked to temperature dynamics. Perhaps when controlling for changes in hydrology and air temperatures, a real impact of sunshine can be extracted from the data which, in its current state, has otherwise been obscured by noise.

Although the data analysis submitted here is only the tip of the iceberg, it theoretically already has enough weight to steer how the landscape at the Kalterbach is understood. The factors driving temperature increases should be reconsidered in light of this data; it helps to nudge stewards of this water body to asks and answer the more informed questions. The GSNs installation opens a world of possibility by providing data that can be used to answer increasingly complex questions. In this way, this GSN does seem relevant for environmental decision makers in the continued renaturation of the Kalterbach. This claim is especially bolstered when one considers the above discussion comes from someone without the specific knowledge that comes from the continued stewardship of a place. The VDM and other stakeholders who have long interacted with the Kalterbach are in a much better position to contextualize this data than the writer of this thesis. They are aware where various tributaries feed into the stream, potentially bringing with them colder waters, or where changes in water depth or speed could shift the degrees on direction of the other. The data here gives these actors more authority in directing renaturation and empowers them to promote the wellbeing of the Kalterbach to a more diverse audience.

5.4 Relevance for Land Governance

At a broader systems level, GSN and IoT theoretically have major implication in shifting how we relate to land or non-human systems and ecologies. The key feature of this change centers around the idea of agency and who we afford it to [9, 12]. Society at large has begun to realize the interdependence between nature and ourselves and as such come to understand that the health of the environment cannot be extracted from the health of humanity. In response to this awakening, new work has emerged to incorporate nature into our human systems of governance [20, 61]. This can only be done if we somehow imbue an agency to nature so that it can participate within the many existing structures of governance we have created. Imagined as a form of translation, IoT has good promise to encourage this agency.

Approaching the GSN at the Kalterbach with this framework in mind, we can begin to imagine how this might play out in a practical sense. In an earlier period, the renaturation would have gone on logic and the recommendation of stakeholders who know dynamics at the river well. If these stakeholders were to testify they could be considered as speaking on behalf of the Kalterbach, but very easily - even if they came with the best intentions - their testimony could be undercut with doubt and dismissed as serving ulterior motives or lacking a rigor. To extend a metaphor, in court, a second hand account of robbery naturally does not hold as much weight as someone who witnessed the crime itself. However, in the case of the renaturation of the Kalterbach, how can you get a first hand account of a rewilding's impact? Data collection through IoT shifts the responsibility of proving harm from a second hand account and moves it closer to the actual system in question. The line of communication between human decision makers and the natural systems they are trying to influence becomes real-time and more easily interpretable. Although the project still remains in its early phases, the data collected at the Kalterbach does seem to encourage agency to the water body. In conversations with stakeholders, analysis showing which physical landscapes along the stream lead to heating or cooling has changed the calculus of which renaturations they should encourage there. Specifically, the realization that the renaturation areas does not seem to have a very large impact on heating or cooling regardless of sunshine hours changes approaches and arguments around the future layout of the stream. Even the simple fact that the water along the Kalterbach *cools* from its source at the Feldmochingersee goes against all expectations from stakeholders and shows the powerful knowledge that this GSN was able to facilitate.

Another way this data increased agency of the stream and changed how stewards of the Kalterbach interacted with the water body revolve around real time monitoring. The dashboard set up on Grafana was regularly checked. Although the intention here was primarily to monitor the GSN and ensure no issues with the network, a secondary impact was the regular monitoring of heating dynamics and water level changes. Whereas before, registering changes in Kalterbach necessarily was limited to when you physically were there - lounging along its banks, going for a swim, or fishing - now real changes at the Kalterbach could occupy your attention with a few clicks on your computer whenever you wished to know. Stakeholders at the VDM would in fact do this regularly, just as a means of knowing how the weather at a certain time was impacting things. To someone without a connection to the Kalterbach, you may be wondering, “so what?”, but imagine if this capacity could be transferred to a more robust, shared natural resource such as the Amazon, the Gulf Stream, or the Great Barrier Reef. If we could theoretically offer IoT data on the severity of drought in various parts of the Amazon, freely accessible to anyone in the world 24/7, how would people’s relationship to that resource change? How might they relate their current wellbeing in the context of the wellbeing of that very important system? How does that real time understanding connect them to this faraway place and encourage them to behave differently? Governance is built on the individual opinions, knowledge, and actions of people. By expanding the understanding of the world in this way, it is not science fiction to suggest it would change our ideas of how we should steward the landscapes around us and connect us more deeply to non-human realities.

Finally, the GSN highlights another reality of natural systems monitoring and offers a promising solution to this conundrum - how do we incentivize care for these ecological systems even when they are inherently independent from capital markets? The capitalistic system which manages the worlds wealth and distributes large amounts of power among humans pays little heed to the wellbeing of non-human experiences. Unless the ecology in questions can somehow be exploited for capital gain (forests for wood production, oceans for fish, etc), there exists little motivation to direct capital or addition goods towards them. Until recently, in western societies, protections for nature were purely the responsibility of the state and even still, do not afford large helping budgets. This fact requires that ecological solutions provide the largest cost-to-benefit ratio and deliver these solutions at a minimal price point. As demonstrated in this 700 €network, GSNs seem capable of this and should only continue to decrease in costs as the technology grows more and more common place. This represents a huge win for ecological monitoring. If GSNs can be scaled to a standard practice in environmentally concerned projects, nature systems, empowered by loads of high quality data, would hold more influence in the governance of the future. Government led programs such as the European Habitat Directive which direct funds for the renaturation of the Kalterbach, should wisely encourage the proliferation of IoT and other technologies that scale (and therefore decrease the costs of) environmental monitoring. Not only would this improve the quality of such programming, it would also hasten the technologies uptake by introducing pressures from governmental organizations.

As a whole, this GSN at the Kalterbach exemplifies, in more ways than one, how IoT networks play an important role in shaping the future of land governance. A good deal of promise exists in IoT to shift how we think about and engage with the natural world. Our current climate crisis should be a clear enough indication that more effective ways of understanding the environment must be developed and more broadly implemented; IoT appears to fulfil at least part of this need.

6 Conclusion

While simultaneously directing attention towards the on-going challenges facing IoT adoption for environmental monitoring, the installation of the network at the Kalterbach demonstrates the utility of this technology and can be used as a model project to understand GSNs and their implications on land and land governance. Specifically explored in the context of open-nature data collection for use at local and municipal levels, the network identifies both the democratizing potential of IoT in this use case and the difficulties associated with installing a network in remote outdoor settings. Generally, the GSN at the Kalterbach can be considered successfully installed and the potential for this data to positively inform environmental decision making was clearly demonstrated. The network was created in collaboration with various stakeholders responsible for the streams renaturation and this approach seemed to help promote the success of the network as well as the future relevance of the data. As a whole, this thesis can be seen as a feasibility study into GSN and several lessons learned have been recorded as a means of encouraging and informing future environmental monitoring schemes using IoT.

The physical installation of the network provided an opportunity to understand how IoT technologies in the open-nature setting can continue to be moved from theory into practice. Although IoT is a fairly established, there remains much practical creativity in how individuals can and should be adopting it. This thesis demonstrated several challenges associated with the current technology in the field of environmental monitoring and this helps us to direct further research or market development to improve devices. Hardware challenges seem to be the greatest problem still facing IoT for this use case. While theoretically the sensors could record data for many years without maintenance or battery replacement, the loss of several sensors due to hardware malfunctions proves that the technology is not yet running at its full potential. Hardware which withstands long term, outdoor monitoring is a priority for future GSN development. While at a higher budget, it is reasonable to assume that hardware durability increases, the market could consider other solutions such as customizable hardware and casing fit to the environmental monitoring use case. Because collecting ecological data however does not have the support of capital markets, ensuring that costs to install a GSN remain low while simultaneously delivering durable sensors will prove to be a worthwhile challenge.

Several months after installation, the data from the network was used to demonstrate its utility in informing environmental decision making. Although many additional analysis's could foreseeably be undertaken, the actual analysis presented represents the wide world of possible new knowledge gleaned from such a system. The data processing here provided insight into the areas of heating and cooling along the stream; by analyzing the data through different constellations and contexts, various insights could be brought to light. By looking at individual sensors in isolation, absolute temperatures for various locations on the Kalterbach could be recorded as well as how those temperatures change throughout the day. For a two week heatwave, the average temperatures in a 24 hour period were collapsed into a single visualization for each sensor device. This showed a day night periodicity along all points on the stream with high temperatures being recorded just before sundown and lows being seen just before sun rise. Moving from individual points to broader systems dynamics, the average temperatures for this heatwave for individual points were considered against the average temperatures for the entire stream. An interpolation of the temperatures in between sensors on the Kalterbach then provide an idea of change across the entire course of the water resource.

The raw data from our GSN sensors were then combined with other openly accessible data for sunshine hours. This highlighted the emergent power of the network when considered against additional variables. The resulting analysis was then used to demonstrate how stakeholders could employ the network to inform decision making for renaturation. Although more factors should be accounted for in the future, the data in its current form suggests that the addition of dragonfly windows would not increase water temperature just based on increased solar radiation alone. New questions can be formulated around the renaturation with this data in mind, nudging decision makers closer to the most informed future for the stream as possible. Incorporating water level and hydraulic modeling represents a promising route for further analysis of the data.

The relative affordability of the technology in consideration with the powerful results it delivers are a strong argument for its continued proliferation in land management and governance. GSNs provide powerful, scalable insights for systems which otherwise do not receive enough time and attention. Monitoring schemes using this technology help to give a voice to nature and translate ecological happens into a human consumable and broadly communicable form. This fact could help to incorporate nature into existing systems of governance for the benefit for the shared wellbeing of both humanity and the planet. The proof provided by this thesis that such projects are no longer just for highly funded institutions, but that these benefits can also be harnessed even at a local and municipal scale point towards a larger systems level shift waiting to be harnessed.

We need not look far to notice that creeping feeling that our home on this pale blue dot has been thrown into a worrying imbalance. At what point did we, humanity, mentally divide ourselves so far from the natural world that we pushed ourselves to this existential crisis; how have we allowed the continued violent exploitation of these life giving systems which we stand on and brazenly call a home, which feed us, which give us oxygen we breath and not yet seen their abuse as self-abuse? Although collectively as a species we must reconsider our relationship to the external world - the external self - and encourage new systems of commerce and being, technological developments can help move us along towards that more vivacious future. While remaining healthy skeptical to the lure of technoidealism, this thesis substantiates the claims put forward in a growing corpus of work that IoT can be leveraged in such a way that repairs our relationship to the world around us. In recent years, a growing imagination has emerged which challenges the trope that a healthy world is a world without humans, that somehow humans are an inherent enemy against this green earth. Doesn't this narrative only further serve to violently and naively cut us out of the natural systems which we are so deeply a part of? Instead, let us put forward a world where we see ourselves as collective stewards of our planet and where we cannot ignore the sameness of ourselves and nature. Perhaps IoT offers one mean, among many means, of communicating that to ourselves, of translating the kaleidoscopic, much-too-complex language of nature into something we humans can begin to comprehend. This task - to find companionship with the many ecologies around us, to build empathy with the things which initially seem foreign from ourselves - should be seen as the eternal work of our species. With this vision guiding us, the future takes on a brighter cadence.

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