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Dissertation

Jannik Schilling

Potentials of open source and open data in geodata-driven, integrated water management

PROFESSUR **Wasserwirtschaft**

Universität Rostock

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Vorwort

Das integrale Management von wasserwirtschaftlichen Ressourcen und dazu erforderlichen technischen Systemen erfordert die strukturierte Erfassung, Verwaltung und Verarbeitung umfassender Datenbestände. Für die Verarbeitung von Daten mit Raumbezug sind Geoinformationssysteme und darauf aufbauende Softwareprodukte unabdingbar. Trotz weit entwickelter Technologien zur Datenerfassung und Verarbeitung ist die Digitalisierung in der Wasserwirtschaft noch ausbaufähig. Ein großes Hemmnis für die konsistente Datenverwaltung sind regionale, sektorale und akteurspezifische Heterogenitäten in der Datenhaltung, proprietäre Daten und Software sowie fehlende digitale Kompetenzen auf der Akteursebene.

Ein zentraler Ansatzpunkt zur Überwindung dieser Hindernisse ist die konsequente Nutzung und Bereitstellung offener Daten und offener Software. Das Thema „Open“ gewinnt in den letzten Jahrzehnten in Wirtschaft, Verwaltung und Wissenschaft einen zunehmenden Stellenwert. Open Source, Open Access, Open Science, Open Government, Open Innovation, Open Educational Resources, Open Data und viele andere Wortschöpfungen bekunden das gesamtgesellschaftliche Interesse an einem freien Zugang zu Wissen, Daten und Werkzeugen zu ihrer Nutzung. Auch die Wasserwirtschaft bewegt sich unter dem Schlagwort „Wasserwirtschaft 4.0“ und im Kontext der durchgängigen Digitalisierung aller Prozesse in Richtung Offenheit.

An dieser Stelle setzt die vorliegende Arbeit an. Durch Nutzung offener Software und offener Daten entwickelt Herr Schilling digitale Werkzeuge zur Verwaltung, Planung und nachhaltiger Nutzung von Wasserressourcen.

Dies wird ergänzt durch die Abstimmung einheitlicher Datenstandards (siehe Band 133) und gezielte, berufsbegleitende Schulungsformate zur Umsetzung. Die Arbeit adressiert damit direkt die europäischen, nationalen und sektoralen Digitalisierungsbemühungen und liefert überzeugende Argumente und Beispiele für ein offenes Geodaten-management in der Wasserwirtschaft und darüber hinaus.

Prof. Dr.-Ing. habil. Jens Tränckner

Universität Rostock

Traditio et Innovatio

Aus der Professur für Wasserwirtschaft
der Fakultät für Agrar, Bau und Umwelt

Potentials of open source and open data in geodata-driven, integrated water management

Kumulative Dissertation

zur Erlangung des akademischen Grades Doktor der Ingenieurwissenschaften (Dr.-Ing.)

an der Fakultät für Agrar, Bau und Umwelt der Universität Rostock

vorgelegt von M.Sc. Jannik Schilling
aus Bamberg

Rostock, 2025

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Abstract

English version

Natural water bodies – rivers, lakes, and seas – are habitats for numerous animal and plant species. At the same time, they are used in many ways as part of the infrastructure created by humans. Water management authorities are therefore faced with the task of reconciling usage interests and nature conservation while at the same time ensuring protection against hazards (e.g., flooding after heavy rainfall, adverse effects of water shortages during periods of drought). This task is overlapped by challenges posed by climate change and long-term land use changes, which have significant impacts on catchment hydrology.
Due to functional interconnections between different fields of water management as well as to other sectors (agriculture, urban and regional planning, energy sector), holistic approaches are needed that weigh up the various, potentially competing goals and possible solutions and prioritize them where necessary. Such concepts, e.g. "integrated water resource management", "integrated river basin management", blue-green infrastructure, etc., have been the subject of research for several years. Their implementation requires cooperation between water management stakeholders, comprehensive, reliable, and openly accessible spatial information, and suitable digital tools to process this data. In this context, this cumulative dissertation highlights the potential of open geodata and open source software for water management.
Geodata are collected and provided by a wide variety of institutions such as public authorities, research institutions, associations, and companies. Accordingly, the variety of data formats, licenses, and types of provision via data portals, data services or Web GIS applications is large. However, their accessibility and, in some cases, restrictions regarding data use can pose a significant hurdle in practical application. In projects

such as OpenStreetMap (OSM), volunteers make user-generated geodata freely available for any purpose. However, data quality and inconsistency may pose a significant challenge here. Nevertheless, open data has enormous potential to optimize integrated water management concepts and planning processes, for example by closing information gaps or making them visible in the first place. With an application example from the research project **PROSPER-RO**, the thesis illustrates how OSM data can be used to generate a high-resolution spatial dataset for wastewater generation in the urban-rural area surrounding the city of Rostock.

In the processing of such geodata, geographical information systems (GIS) and modeling software are the essential digital tools in water management. Besides proprietary software, numerous open source programs are also available in both software groups. In the field of GIS, QGIS in particular has established as a popular open source alternative in recent years. Programming interfaces to R and Python allow users to create their own extensions – so-called "plugins". Three of such QGIS plugins have been developed and published in the framework of this thesis:

- WaterNetAnalyzer – Processing tools for constructing hierarchical water networks (watercourses, sewer networks, etc.) and for network tracing
- generate_SWMM_inp – A tool for importing and exporting data to the open source modeling software SWMM
- OSWeGe_tools – A tool for analyzing topological errors in river-related geodata from regional water and soil associations/ *Wasser- und Bodenverbände*WBV

Further application examples demonstrate the diverse possibilities offered by open source GIS for stakeholders in water management. In the field of coupled hydrological/hydraulic models, numerous applications available today are based on "SWMM", thus demonstrating the innovative potential of open source software in the context of water management.

In addition to the data and tools, trained professionals are required to use them successfully. The final section of this paper presents the **OS-WeGE** project, in which a GIS training program was developed and implemented for employees of water and soil associations in Mecklenburg-Western Pomerania/*Mecklenburg-Vorpommern* (M-V).

German version

Natürliche Gewässer – Flüsse, Seen und Meere – sind Lebensraum für zahlreiche Tier- und Pflanzenarten. Gleichzeitig werden sie in vielfältiger Weise als Teil der von Menschen geschaffenen Infrastruktur genutzt. Wasserwirtschaftliche Aufgabenträger stehen daher vor der Aufgabe, Nutzungsinteressen und Naturschutz miteinander zu vereinbaren und zugleich den Schutz vor Gefahren (z.B. Hochwasser nach Starkregen, Beeinträchtigungen durch Wassermangel in Dürreperioden) zu gewährleisten. Überlagert wird diese Aufgabe von Herausforderungen aufgrund des Klimawandels oder langfristigen Landnutzungsänderungen mit merklichen Auswirkungen auf die Folgen für alle Komponenten des Wasserhaushalts in einem Einzugsgebiet.
Aufgrund der funktionalen Verknüpfungen zwischen verschiedenen Bereichen innerhalb der Wasserwirtschaft, sowie zu anderen Sektoren (Landwirtschaft, Stadt- und Regionalplanung, Energiesektor) bedarf es dabei ganzheitlicher Ansätze, die die verschiedenen, möglicherweise konkurrierenden Ziele und Lösungsmöglichkeiten gegeneinander abwägen und gegebenenfalls priorisieren. Solche Konzepte sind beispielsweise als "Integrales Wasserressourcenmanagement", "Integrales Flussgebietsmanagement", blau-grüne Infrastruktur etc. seit einigen Jahren Gegenstand der Forschung. Voraussetzung für ihre Umsetzung ist die Zusammenarbeit von wasserwirtschaftlichen Akteuren, umfassende, verlässliche, und offen zugängliche, räumliche Informationen, sowie geeignete digitale Werkzeuge zu ihrer Verarbeitung. Die vorliegende kumulative Dissertation beleuchtet in diesem Kontext Potenziale von offenen Geodaten und *open source*-Software für die Wasserwirtschaft.
Geobasisdaten und Geofachdaten werden erhoben und bereitgestellt von unterschiedlichsten Institutionen wie Behörden, Forschungseinrichtungen, Vereinen oder Unternehmen. Entsprechend groß ist auch die Vielfalt an Datenformaten, Lizenzen und der Art der Bereitstellung über Portale, Datendienste oder Web-GIS-Anwendungen. Ihre Zugänglichkeit und gegebenenfalls Nutzungseinschränkungen können jedoch in der praktischen Anwendung eine essentielle Hürde darstellen. In Projekten wie OpenStreetMap (OSM) stellen Freiwillige nutzergenerierte Geo-

daten für jegliche Anwendung frei zur Verfügung. Hier kann jedoch die Datenqualität und Uneinheitlichkeit eine wesentliche Herausforderung darstellen. Dennoch steckt in offenen Daten ein enormes Potenzial, integrale wasserwirtschaftliche Konzepte und Planungsprozesse zu optimieren, beispielsweise indem sie Informationslücken schließen bzw. solche überhaupt erst sichtbar machen. Mit einem Anwendungsbeispiel des Forschungsprojekts **PROSPER-RO** zeigt die Arbeit, wie mithilfe von OSM-Daten ein räumlich hochaufgelöster Datensatz für das Schmutzwasseraufkommen im Stadt-Umland-Raum der Stadt Rostock generiert werden kann.
In der Verarbeitung dieser Daten sind Geoinformationssysteme (GIS) und wasserwirtschaftliche Modelle die zentralen digitalen Werkzeuge. Bei beiden Softwaregruppen stehen neben proprietären auch zahlreiche *open source*-Programme zur Verfügung. Im GIS-Bereich hat sich in den letzten Jahren vor allem QGIS als *open source*-Software etabliert. Über Programmierschnittstellen zu R und Python können eigene Erweiterungen, sogenannte "*Plugins*" erstellt werden. Drei solcher QGIS-*Plugins* wurden im Rahmen dieser Arbeit entwickelt und veröffentlicht:

- WaterNetAnalyzer – Verarbeitungswerkzeuge für den Aufbau hierarchischer Gewässernetze (Fließgewässer, Kanalnetzsysteme etc.) und zur Netzverfolgung
- generate_SWMM_inp – ein Werkzeug zum Import und Export von Daten in die *open source*-Modellierungssoftware SWMM
- OSWeGe_tools – ein Analysetool für topologische Fehler in Gewässer-Geodaten von Wasser- und Bodenverbänden

Weitere Anwendungsbeispiele zeigen die vielfältigen Möglichkeiten durch *open source*-GIS für Akteure der Wasserwirtschaft. Im Bereich gekoppelter hydrologisch/hydraulischer Modelle bauen zahlreiche heute verfügbare Anwendnungen auf "SWMM" auf und belegen so das Innovationspotential von *open source*-Software im Kontext Wasserwirtschaft. Neben den Daten und Werkzeugen selbst braucht es geschultes Personal, um diese erfolgreich einzusetzen. Der letzte Abschnitt dieser Arbeit stellt das Projekt **OSWeGE** vor, in dem ein Weiterbildungsprojekt für Mitarbeiter*innen der Wasser und Bodenverbände in Mecklenburg-

Vorpommern entwickelt und durchgeführt wurde.

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Abbreviations

ALKIS German official real estate cadastre information system/*Amtliches LiegenschaftskatasterInformationssystem*

AI artificial intelligence

API application programming interface

BOAI Budapest Open Access Initiative

CAD computer-aided design

CC Creative Commons

CLMS Copernicus Land Monitoring Service

DEM digital elevation model

DFSG Debian Free Software Guidelines

DNG German law on the use of public sector data / *Datennutzungsgesetz*

DOI digital object identifier

DWA German association for water management, wastewater and waste / *Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall*

DWD German meteorological service/*Deutscher Wetterdienst*

DSS decision support system

EGovG German law on open government data/*E-Government-Gesetz*

FSF Free Software Foundation

GeoZG German geodata access act / *Geodatenzugangsgesetz*

GIS geographic information system

GML geography markup language

GPL GNU General Public License

GUGV German law on the formation of waterway maintenance associations/*Gesetz über die Bildung von Gewässerunterhaltungsverbänden*

GUI graphical user interface

IPCC Intergovernmental Panel on Climate Change

IFG German freedom of information act/*Informationsfreiheitsgesetz*

KML keyhole markup language

LAiV State authority for the Interior of M-V/*Landesamt für innere Verwaltung M-V*

LAWA German national/federal state working group on water/*Bund/Länder-Arbeitsgemeinschaft Wasser*

LID low impact development

LULC land use and land cover

LUNG state authority for environment protection / *Landesamt für Umwelt, Naturschutz und Geologie Mecklenburg-Vorpommern*

LUP land-use plan

LWaG state law on water ressources/*Landeswassergesetz M-V*

M-V Mecklenburg-Western Pomerania/*Mecklenburg-Vorpommern*

ODC Open Data Charter

OGC Open Geospatial Consortium

OKF Open Knowledge Foundation

OSI Open Source Initiative

OSM OpenStreetMap

POI points of interest

PE population equivalents

SDG Sustainable Development Goals

SPS sewage pumping station

SWMM Stormwater Management Model

UGC user-generated content

UIG German law on environmental information/ *Umweltinformationsgesetz*

UrhG German copyright act/ *Urheberrechtsgesetz*

URI uniform resource identifier

VGI volunteered geographic information

WBV regional water and soil associations/ *Wasser- und Bodenverbände*

WFS web feature service

WHG German water resources law/ *Wasserhaushaltsgesetz*

WMS web map service

WFD EU Water Framework Directive

WWAV Warnow Water and Wastewater Association/ *Warnow-Wasser- und Abwasserverband*

WWTP wastewater treatment plant

W3C World Wide Web Consortium

Symbols

A	area	m^2
f_R	"Rural" factor	-
q_C	discharge rates for commercial areas	$\mathrm{L\,m^{-2}\,d^{-1}}$
q_I	discharge rates for industrial areas	$\mathrm{L\,m^{-2}\,d^{-1}}$
q_R	discharge rates for residential areas	$\mathrm{L\,person^{-1}d^{-1}}$
Q	discharge / flow	$\mathrm{m^3\,s^{-1}}$
NI	number of inhabitants	persons

1. Introduction

1.1. Motiviation

This dissertation was written within the framework of two research projects at the professorship of water management at the University of Rostock. The project **PROSPER-RO** (2018–2023), funded by the German federal ministry for education/*Bundesministerium für Bildung und Forschung* (BMBF), focused on urban and regional planning. The aim of the project was to develop digital tools and data bases for land use planning of large cities and their surrounding areas as part of an "integral" and GIS-based decision support system (DSS). The integral character of the DSS was achieved through i) a combined and cross-sectoral approach to assessing the impacts on circular economy, on urban water management infrastructures, as well as the impact on natural landscapes by using the concept of ecosystem services, and ii) a combined, uniform planning for both urban and rural areas across administrative boundaries. Using the example of the *Regiopolregion Rostock* the DSS was used to design and evaluate future land use development scenarios. A characteristic feature of the project was the exchange and combination of geodata from a wide range of project partners from public administration and the private sector, as well as the processing and visualization of this data using geographic information systems (GIS).
Addressing the challenges of climate change for water management stakeholders in Mecklenburg-Western Pomerania was the guiding topic of the project **OSWeGe** (2023-2025), funded by the German federal ministry for environment protection/*Bundesministerium für Umwelt, Klimaschutz, Naturschutz und nukleare Sicherheit* (BMUKN). Since the state's water bodies are affected by both drought and temporary flood runoff after heavy rainfall due to long-term climatic changes, the re-

sponsible regional water and soil associations (WBV) will have to adapt their water management practices. Again, the entire planning process for maintenance or construction measures on water bodies is based on geodata processed in GIS. Therefore, the project developed and implemented a training program regarding GIS applications for water management at the WBV.
In both projects, innovative ideas could only be developed or implemented because data was openly accessible or because open software could be adapted for these ideas. However, both projects also revealed that there are numerous barriers and pitfalls when dealing with open source software and open data.

1.2. Current research fields and objective of the thesis

Open source and open data represent a very diverse field of research. Over the past 20 years, the framework conditions that apply today have been created at various levels for their use and distribution. At the technical level, open standards and open digital tools have been developed by open source communities, networks and research projects. In view of various crises for society as a whole (climate change, pandemics etc.) these efforts have been an important contribution to a resilient civil society (cf. Open Knowledge Foundation Deutschland e.V. (OKF-DE), 2020). At the legal level, new EU legislation and its implementation in national law have paved the way for “openness”, particularly in public administration. Currently, the focus of research is shifting toward operational implementation, removing obstacles, and consolidating data resources. The associated objective in Germany primarily is to advance digitization of public administration and make better use of the potential of open data and software (Weke et al., 2024b). The German government’s 2021 open data strategy (BMI, 2021) specifies four fields of action for this purpose:

1. high-performance and sustainable data infrastructures,

2. increasing innovative and responsible data use,

3. increasing data literacy and establishing a new data culture, and
4. the role of the state as a pioneer of the new data culture.

In the course of this development the water sector is also shifting towards digitalization and must therefore create suitable framework conditions (DWA, 2020a). At the same time, the involved actors are facing major challenges – dealing with climate change, demographic trends, etc. The services provided by the water sector must be adaptable to changing natural conditions and social requirements through flexible infrastructures (DWA & DVGW, 2021).

Digital tools for automation in administration, planning, protection and sustainable use of water resources are being researched under the buzzword "Water Management 4.0.". However, when compared with other sectors, the level of digitization in water management is rather "moderate", according to a study by the German Federal Environment Agency (cf. Holländer et al., 2020). The potential of the developments of "Water Management 4.0" has been realized to varying degrees so far, in particular by planners, lower water authorities and small associations or companies. The study reviews opportunities and challenges of linked (data) systems in water management with a focus on the benefits for citizens and environmental protection. A big potential is seen for example in the improvement of flood risk management. In operational flood protection, linked data from sensor-based systems could enable advanced condition monitoring of flood protection systems. Coupled control systems for dams and urban drainage e.g. with remote sensing data could be used as early warning systems (DWA, 2020a; Holländer et al., 2020). The varying degrees of development in digitization across different regions and the resulting clash of individual solutions are described as challenging. The harmonization and standardization of data and interfaces therefore play a key role in successfully realizing the potential. To achieve this, new services, data products and applications must be developed and made openly available.

This dissertation addresses the need at the intersection of the mentioned fields of research, but focuses on spatial data, GIS and modeling. The objective of the thesis is to evaluate the potential of using open geodata and open source GIS software for water management issues, by reviewing and developing and implementing practical solutions.

1.3. Structure of the thesis

The thesis is structured in four main parts. Each part is defined by a central question (in italic letters):

1. *What characterizes "open" and which benefits can be retrieved from open source and open data in general?* Chapter 2 therefore provides a comprehensive literature review for a suitable definition of "openness", starting with the history of the terms "open data" and "open source". The section gives an overview of the different license types used in open data and open source projects and describes advantages which are related to them, as well as current legal developments and examples of available open data.

2. *Which of the findings from chapter 2 (potentially) apply for the context of water management in particular?* Chapter 3 outlines the field of action in water management with its objectives, stakeholders and challenges. A detailed view is taken on so-called "integrated" water management approaches and the question why these would especially profit from openness in terms of data and software. Afterwards, two central types of tools in water management, GIS and modeling software, are presented to underline the importance of open source in software development.

3. *How can open (geo-)data efficiently be combined with other data sources to improve existing concepts and models?* Chapter 4 presents two open source application examples developed and published within the framework of the projects PROSPER-RO and OSWeGe.

4. *How can this potential be realized?* Chapter 5 shows how training with open source software can contribute to capacity building in water management, especially for local or regional authorities. The chapter is based on interviews, surveys and practical experience from the project OSWeGe.

Finally recommendations are given for the use of open data and open source software.
The thesis comprises three peer-reviewed publications:

(a) Schilling, J., & Tränckner, J. (2020). Estimation of wastewater discharges by means of OpenStreetMap data. *Water*, *12*(3), 628. https://doi.org/10.3390/w12030628

This first paper demonstrates how open data like OpenStreetMap can be used in water management. For the optimization of sewer networks and integration of water management in urban planning, estimations of wastewater discharges at a high spatial resolution are a key boundary condition. In many cases, these data are not available or, for reasons of data protection and company secrecy, the data are not accessible for research purposes. Therefore, procedures are needed to determine the volume of wastewater with high spatial resolution, based on freely accessible data. The presented approach uses mainly OSM data, combined with a dataset of the German official real estate cadastre information system/*Amtliches LiegenschaftskatasterInformationssystem* (ALKIS), to estimate the volume of wastewater on a building level.

(b) Schilling, J., & Tränckner, J. (2022). Generate_SWMM_inp: An open-source QGIS plugin to import and export model input files for SWMM. *Water*, *14*(14), 2262. https://doi.org/10.3390/w14142262

The publication presents a free and open-source QGIS plugin to generate Stormwater Management Model (SWMM) models from geodata and to import existing SWMM input files into QGIS. SWMM is an open-source model and software developed by the US EPA for the simulation of rainfall-runoff and routing in water bodies, sewer systems and wastewater infrastructures. It has been applied in numerous practical works and research projects. For a new SWMM model, objects such as nodes, links and catchments can either be drawn via SWMM's graphical user interface (GUI) or specified manually in a plain text file in ".inp" format ("input file"). Since the required data regarding sewer geometries and river systems are usually available as spatial data in a GIS environment, there is a need for user-friendly interfaces for the model setup. The paper describes the structure of the developed plugin as well as an application example to demonstrate its basic features and usage.

(c) Schilling, J., Steiger, A., & Tränckner, J. (2025a). Spatial tools for river management: Capacity building through GIS. *Water Policy*, *27*(7), 737–751. https://doi.org/10.2166/wp.2025.011

This article deals with various impacts that affect rivers and their ecosystems. These impacts include various human activities, as well as climate-related issues. Such impacts are characterized by complex (inter-)dependencies and processes which are in some way spatially related in the river basin. Addressing these spatial aspects is therefore decisive for successful river management. This requires according data and tools as well as capable stakeholders to use them. The publication depicts challenges in river management with their spatial dimension, elaborates the central role of GIS in addressing these challenges and derives the need of GIS related capacity building for stakeholders.

Papers (a) and (b) are integrated in the thesis (chapter 4) as published. By contrast, due to the structure and logic of the dissertation, excerpts of paper (c) are integrated in various sections of the chapters 3 and 5. The entire paper (c) can be found in annex B of the thesis. For the reasons of readability, the referenced literature of each the publications is listed in the general list of references and the enumeration of the chapters, figures and tables follows the general style of this thesis.

2. Theoretical framework

This chapter starts with explaining key terms and basic concepts used in the thesis. In the standard specification ISO/IEC 2382:2015 "information" are defined as "knowledge concerning objects, such as facts, events, things, processes, or ideas, including concepts, that within a certain context has a particular meaning". If information is available in a form that can be interpreted by humans or machines, i.e., it has a standardized coding using bits, signals, characters, character strings, etc., it is referred to as "data" (e.g. in ISO/IEC 2382:2015: "reinterpretable representation of information in a formalized manner suitable for communication, interpretation, or processing; Data can be processed by humans or by automatic means"). Information with a direct or indirect spatial reference on Earth, the "georeference", is referred to as "geoinformation", and consequently, information encoded in digital form is referred to as "geodata" (e.g. defined by DIN ISO/IEC 2382:2015 or § 3 of the German geodata access act / *Geodatenzugangsgesetz* (GeoZG)). Geodata is "open" (following the open definition of the Open Knowledge Foundation (OKF) (2015)) "if anyone can freely access, use, modify, and share for any purpose". However, that's just one of the many definitions of the term, mentioning some its benefits. This chapter delivers insight into the history of "open", related licenses, legal framework and potentials.

2.1. Open Data and Open Source

The prefix "open" is used in various contexts today: "Open source software", in contrast to proprietary or closed-source applications, is characterized by open source code and, as a rule, software development that is promoted and practised by the user community (Peterson, 2018;

Tennant et al., 2020). With “open (source) hardware”, 3D printing designs or construction plans and documentation of physical objects are made freely available (Bonvoisin et al., 2017). The term “open government data” has become established, particularly in relation to data from public administration and politics. The act of making such administrative or governmental data freely available by default in order to act with transparency and foster participation are referred to as “open government” (Badiee et al., 2021). In the publication business of mainly scientific articles, “open access” has become an established label for papers which can be read and downloaded by anyone with internet access. Teaching materials which are available on online platforms can be found with the keyword “open educational resources” (Davies, 2019). The idea of free access and free use is being applied in more and more areas (open science, open content, open design, open culture). Consequentially it seems appropriate to speak of an open movement, or to use overarching terms such as “open knowledge” (OKF, 2015) which incorporate the components mentioned above. For example, Coetzee et al. (2020) speak of a “virtuous circle” of openness (see 2.1) in which many different parts not influence each other, but make the circle incomplete when missing.
This diversity is also reflected in the various definitions and criteria of openness that have been formulated over time. Therefore, the following section is devoted to the history of the term.

2.1.1. History of the term “open”

The attribute “open” can be traced back to various social and political movements of the 20th century, which coined this term based on their own philosophy and criteria. With regard to software, the “free software” movement can be seen as a starting point. Emerging from the hacker culture and the academic software development environment of the 1970s, the movement arose in the 1980s when the first companies released software under restrictive licenses and began to keep the source code secret (Tennant et al., 2020). The movement focused on the rights and autonomy of software users. This was linked to the call for three

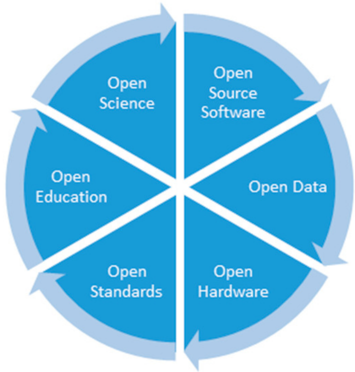


Figure 2.1.: Circular concept of different aspects of openness, where each component can not be independent from the others. Figure from Coetzee et al. (2020)

fundamental freedoms, for which the source code must be available: the freedom to modify a program according to the users needs, the freedom to copy and redistribute software, as well as the freedom to enhance or correct a program and publish these improvements. These three freedoms also correspond to the definition of free software as originally formulated by the Free Software Foundation (FSF), founded by Richard Stallman in 1985 (FSF, n.d.).Later, the freedom to study the functionality of a program and to use it in any way for any purpose was added. The movement's flagship project is the GNU Project with the free GNU operating system and the license (see 2.1.2) of the same name (Stallman, 2009).
The term "open source" first appeared in 1998, when various software developers in the free software movement were looking for a marketing term that, unlike the ethically or morally, and politically charged term "free software", was more compatible with commercial activity, mainly through permissive licenses. Due to the ambiguity of the word "free", it

was also intended to clarify that the focus was not the price[1] of software or source code, but on the open, community-driven development process (Tennant et al., 2020). The original suggestion for this name came from Christine Peterson, although the term was mainly coined and popularized by the founding team of the Open Source Initiative (OSI)[2], Eric S. Raymond, Bruce Perens, and other software developers associated with the OSI (Peterson, 2018). The OSI formulated an open-source definition with ten criteria derived from the Debian Free Software Guidelines (DFSG) in the “Debian Social Contract” (SPI, 2022) written in 1997. The criteria of the OSI in version 1.9 from 2007 include:

1. the right to freely distribute the software, even in parts,
2. the right to access the source code and distribute it and
3. permission to further develop the work and parts of it under the same license (for licenses, see chapter 2.1.2).
4. For reasons of integrity, changes to the original source code may be restricted, or it may be required that the original and derivatives be clearly identified by their names or version numbers.
5. An open source license may not exclude any persons or groups from using the software.
6. An open source license may not contain any restrictions on the intended use of the software.
7. An open source license applies to everyone who receives the software without the obligation to purchase additional licenses.
8. An open source license may not prescribe specific software or
9. contain restrictive conditions for the use of other software. It may also not require that other programs delivered together with the open source software are also open source.

[1] Even though the free software movement always emphasizes that free software does not necessarily have to be free of charge (i.e., “freeware”). The slogan “Free as in free speech, not free as in free beer” (e.g. Stallman, 2009) is often quoted in this context.

[2] also founded in 1998

10. An open source license may not prescribe specific technology or hardware as a prerequisite.

(OSI, 2024).
While criteria 1-3 are consistent with the free software philosophy, the possible restrictions on modifications in point 4 contradicts the FSF's "ethical imperative" of user freedom. According to the FSF, the option of using licenses without copyleft is also incompatible with the idea of free software (Stallman, 2009). Therefore the FSF continues to emphasize the distinction between "free" and "open source" in its rather purist philosophy. Nevertheless, projects that combine aspects of both movements are often assigned combinations of the two terms. Common abbreviations are FOSS – free and open source software – or FLOSS – free/libre and open source software (Tennant et al., 2020). One example is the FOSSGIS e.V. in Germany, founded in 2001, which is committed to the development of free software in the GIS field and the promotion of open geodata. (FOSSGIS, n.d.). In general, "open source" is more commonly used today (Tennant et al., 2020), for example in the European Commission's open source software strategy (European Comission, 2020)
Also, the term "open data" or, more generally, "open content" which came up later, partly goes back to open source ideas and is closely linked to free access to information sources through the development of the internet as a medium (Tennant et al., 2020). In addition, the origins of the term open data can also be found in the social movements of "open government" – the accessibility of information on administrative procedures and decision-making processes – and "open science" – the accessibility of knowledge sources (Badiee et al., 2021). The developments in the various movements overlap both in terms of timelines and their relevance to open data. Some key events will be highlighted here.
The Budapest Open Access Initiative (BOAI) of 2002 represents a milestone in the open publication of scientific results and reports. It led to a declaration by numerous scientists and institutes, which established criteria for the term "open access" and proposed two publication strategies. According to the declaration, journal articles could either be stored in freely accessible electronic archives ("self-archiving") or published

in open access journals to meet the requirements (BOAI, 2002). The Bethesda Statement on Open Access Publishing, published in 2003, and the Berlin Declaration on Open Access to Knowledge in the Sciences and Humanities, published in the same year, also refer to the BOAI with similar definitions of open access (Tennant et al., 2020). For example, the Bethesda Statement reads:

> An Open Access Publication is one that meets the following two conditions:
>
> 1. The author(s) and copyright holder(s) grant(s) to all users a free, irrevocable, worldwide, perpetual right of access to, and a license to copy, use, distribute, transmit and display the work publicly and to make and distribute derivative works, in any digital medium for any responsible purpose, subject to proper attribution of authorship, as well as the right to make small numbers of printed copies for their personal use.
> 2. A complete version of the work and all supplemental materials, including a copy of the permission as stated above, in a suitable standard electronic format is deposited immediately upon initial publication in at least one online repository that is supported by an academic institution, scholarly society, government agency, or other well-established organization that seeks to enable open access, unrestricted distribution, interoperability, and long-term archiving(...)
>
> (Brown et al., 2003)

The specifications of the Bethesda Statement represent a special case of what was later outlined in the general “open definition” for data, content and knowledge by the Open Knowledge Foundation (OKF), founded in 2004. The first version of the definition dates back to 2005. The current version 2.1 covers:

- the open **status** of the work, e.g. in public domain/common property or a corresponding open license. The nine criteria of the

OKF for suitable open licenses take up the essential criteria from the OSI open source definition, but also expand and specify them, for example by prohibiting fixed fees within a license.

- the **accessibility** of the data, as well as associated (meta)information on licenses, authors, etc.,
- **machine readability**[3] of data and
- the requirement for an open **format**[4] for the data (OKF, 2015).

The foundation supports a large variety of open projects, including data, software, hardware and education. Its most prominent project is the software CKAN for open data catalogs (OKF, 2018).
In Europe, directive 2003/98/EC on the re-use of public sector information was a first step towards "open government(al data)". The directive lists different types of public authorities and related documents, to which open accessibility should be applied. An important driver for the concept open government in the USA was the Sunlight Foundation, which in 2007 supported a meeting of the working group in Sebastopol, California. During that meeting, which later became famous as the "Sebastopol meeting", the thirty participants formulated eight principles of open government data. The principles in general cover basic ideas of the definitions listed above (Badiee et al., 2021). For example, like the "open definition" of the OKF, the principles contain accessibility (principle 4) and machine readability (principle 5). The non-discriminatory availability of data in an open format (principles 6 and 7) reflects the criteria of the open-source definition. However stricter requirements regarding data quality are made. Principle 1 demands for completeness of public data, which should be published as primary data (principle 2) and timely (principle 3) (Public.Resource.org., n.d.). Similar principles are contained in the "Open Data Charter" (ODC) which was formulated

[3] Definition of machine readable documents according to Art. 2 (13) of Directive 2019/1024/EU: "a file format structured so that software applications can easily identify, recognise and extract specific data, including individual statements of fact, and their internal structure."

[4] Definition of open formats according to Art. 2 (14) of Directive 2019/1024/EU: "a file format that is platform-independent and made available to the public without any restriction that impedes the re-use of documents."

in 2015 by governments, civil society within the framework of the Open Government Partnership Global Summit in Mexico. The four criteria of the charter are open by default, timely and comprehensive, accessible and usable, comparable and interoperable (ODC, 2015).
In the "open science" movement, a community of researchers, librarian and publishers with the name "FORCE11" developed the so-called FAIR guidelines in 2016. The document contains four central requirements for the reuse of digital research data. According to these guidelines, FAIR data must be

- **f**indable, i.e., be identified by unique identification markers such as a digital object identifier (DOI) in the metadata.
- **a**ccessible: Data and metadata can be retrieved via the identifier using standard protocols, with access restrictions if necessary.
- **i**nteroperable: Data and metadata must be stored in a language that is understandable and accessible (to humans and machines), and references to other data sets must be included.
- **r**eusable: The data contain an appropriate description through metadata and an accessible data usage license, and comply with the usual standards of the respective discipline or community. (Wilkinson et al., 2016).

An additional feature to "open" are links to other data sets with uniform resource identifiers (URIs). Such references create semantic relations which can be used in advanced, automated data analyses. The five-star model, developed by Berners-Lee (2009), therefore assigns the highest possible rating to linked open data. Guidelines for linked open government data have been published for example by the World Wide Web Consortium (W3C) (Bennett & Harvey, 2009).
As the aforementioned examples illustrate, there is a wide variety of definitions for open source and open data, but they share fundamental properties. In each case, the key factors are the accessibility of data or source code and the possibility of using it for one's own purposes (Tennant et al., 2020). This dissertation uses the generally formulated open definition of the OKF which can be applied for both software and data.

2.1.2. Licenses

The development of the term "open" is closely linked to the creation of corresponding licenses for the publication and use of open data and software. It is only through these licenses that users can see what they are allowed to do with the data or software. One main distinguishing feature among open licenses is the copyleft clause or "share-alike". It stipulates that any further developments, including parts of the work, must be placed under the same license as the original work (Miller et al., 2008). This prevents restrictions from being imposed on the use of open-source data or source code by modifying it. Such a clause also prevents open program libraries from being integrated into proprietary software, or open data from being integrated into data sets with stricter copyright (cf. Paderta, 2012). These types of clauses are therefore one of the main causes of incompatibilities between open-source programs or libraries (cf. Sinclair, 2010).

One of the first permissive open-source software licenses is the MIT license developed at the Massachusetts Institute of Technology, although its exact publication date is unknown (Haff, 2019). The first paragraph of the license text contains permission to use, reproduce, modify, and distribute the software, with the sole condition that the license text has to be included with all copies of the software or portions of it, with reference to the copyright holder. The second paragraph excludes any warranties ("without warranty of any kind"). In addition to the classic MIT license, there is also the "X11" variant, which imposes restrictions on attribution for advertising purposes, and the "MIT No Attribution License" version, which does not require copyright attribution (cf. Löwe et al., 2022; OSI, n.d.).

The BSD license family, originally used for the Berkeley Software Distribution (BSD) operating system, is characterized by a comparable structure (rights of use and disclaimer). The oldest version of the open-source license ("BSD 4-clause license") from 1990 contained a so-called "advertising clause", which required the copyright holder to be named when advertising products with BSD-licensed software. Later variants (BSD 3-clause, 2-clause, and 0-clause license) omit this clause (Sinclair, 2010).

The GNU General Public License (GPL) published in 1989 by the FSF and the GNU Project is a copyleft license, as is the revised version GPLv2 from 1991 and version 3 of the license, which has been available since 2006. In a list of provisions, the GPL essentially grants the user the freedoms described above, followed by the exclusion of warranties by the copyright holder, using a wording similar to that of the MIT and BSD license family (Lee, 2007). The variant "GNU Lesser General Public License" waives copyleft, thus also allowing the use of a program library licensed under this license in proprietary programs.
For open content in general, other license types have been developed. A characteristic one is, for example, the modular "Creative Commons" (CC) license system which was developed by the the Creative Commons Corporation. In 2001 the organization was founded by Lawrence Lessig and colleagues from the Stanford University, USA. The main goal of the international non-profit organization is to develop standardized license contracts to enable content sharing with various levels of openness (Kreutzer, 2016). The first set of licenses (version 1.0) was published in 2002. Due to incompatibilities with national law systems, in 2003 adjusted variants of version 3.0 the licenses were published as well as an international version. Currently, Creative Commons (CC) version 4.0 international from 2013 is available (Kreutzer, 2016). The CC-Zero/CC0 variant grants complete freedom for the users. CC BY requires that authors must be acknowledged. The addition "Share-Alike" (CC-SA) corresponds to the copyleft obligation. Furthermore, commercial use can be restricted (CC-NC) or modifications to the text can be prohibited ("No Derivatives", CC-ND). Some of the options can be combined (e.g. CC-BY-SA). (Creative Commons, n.d.-a). The CC license family is often used for open data although this practice has been criticized, because data and databases not necessarily are "creative works" in the sense of a countries copyright (Miller et al., 2008).
For specific use cases there are separate licenses such as the Open Data Commons Open Database License (ODbL) which is applied for the distribution of databases with a share-alike and attribution clause. One prominent example is the data of the OpenStreetMap project (Geofabrik GmbH, n.d.-a). Similarly, the Open Data Commons Public Do-

main Dedication and License (PDDL) and the Open Data Commons Attribution License (ODC-By) apply for databases but without attribution and, in the case of the PDDL, without share-alike (Müller & Weber, 2021). For data and programs published by official bodies, there are country-specific license types, such as the German "*Datenlizenz Deutschland*", which is currently published in version 2.0. The license can be used in two variants, which allow both commercial and non-commercial use cases. With "dl-by-de/2.0" the data provider has to be cited and a link is required to the URL of the original data set as well as to the license text (FITKO, 2016). Changes and edits must be clearly marked, may result in considerable additional effort when users want to combine different datasets (Happ et al., 2022). The "zero" variant ("dl-zero-de/2.0") allows the use of the data without restrictions or conditions. The "*Datenlizenz Deutschland*" is recommended for official open data in Germany (FITKO, 2016), although it has been criticized for being an isolated application which might lead to incompatibilities (cf. Krabina, 2020). The European Union Public License (EUPL) is a copyleft license drafted by the European Commission, developed for the distribution of software. The EUPL is compatible with the version 2 of the GPL. In 2009 version 1.1 of the license was accepted by the OSI (European Comission, n.d.).

In addition to the various approaches to specifying names, usage rights, distribution rights, etc. in license texts, there are also efforts to consider data and program code as public domain, provided that the country-specific legal situation allows this. This approach is motivated in particular by incompatibilities between different open source licenses. One of the most radical approaches, the concept of the "Unlicense" exists specifically for software. Based on the wording of the SQlite project, this declares the software to be in the public domain or grants corresponding rights of use and, with the help of the MIT/X11 clause, excludes any warranty claims by the user against the author or developer (Bendiken, n.d.). Since in Germany the author of a work automatically receives protection of certain rights according to the German copyright act/*Urheberrechtsgesetz* (UrhG) and which cannot be transferred (§ 29 (1) UrhG), it is not possible to release the work completely into the

public domain. However, rights of use which are free of charge can be granted to everyone (§ 32 (3) UrhG, known as the "*Linux clause*"), for example through the CC0 license.
The multitude of licenses and their contracts with legal terminology pose a significant challenge for many data users, developers and authors, which are typically not legal experts. From the user perspective incompatible licenses are a major challenge for the re-use of data or software. A positive example for license harmonization is the "PEGELONLINE" portal (WSV, n.d.), which since 2024 stipulates publishing hydrological information on inland and coastal gauges uniformly under the *Datenlizenz Deutschland – Zero – Version 2.0*, whereas previously various open data licenses were used by the responsible authorities (ITZ, 2024).
At the provider perspective, licensors/developers must consider the advantages and disadvantages of each license type relevant to the application context (Kreutzer, 2016). Therefore, depending on the technical context, there may be guidelines or obligations for the usage of certain types of licenses. Guidelines have for example been provided for open administrative data in Germany (Krabina, 2020). Extensions for QGIS, such as the example in section 4.2 have to published with licenses compatible to the GPL in version 2 or later (QGIS Project, n.d.-a). The Open Data Directive (2019/1024/EU) also emphasizes the importance of clear licensing, which is specified in the Commission Implementing Regulation (2023/138/EU) by explicitly mentioning CC0 and CC-BY 4.0 as examples. With reference to these regulations the German national/federal state working group on water/*Bund/Länder-Arbeitsgemeinschaft Wasser* (LAWA) recommends to publish documents and data with a CC-BY 4.0 license, if possible. Moreover, reports and statistics should use the non-derivative option (ND) (Müller & Weber, 2021). Tools such as the "License Chooser" for the CC license also help to select the right license for the content to be published (Creative Commons, n.d.-b). A similar tool for software licensing is provided by "choosealicense.com" (GitHub Inc., n.d.).

2.1.3. Recent regulative developments in the field of open data

Various changes in European and German legislation have gradually specified the requirements for open data and the associated licenses and formats. The creation of a Europe-wide geodata infrastructure is, for example, the goal of the INSPIRE directive (2007/2/EC) which was legally implemented in Germany by the GeoZG and equivalent laws on the federal state level. According to § 11 GeoZG and § 2 of the accompanying regulation (*Geodatennutzungsverordung*, GeoNutzV), federal geodata is provided free of charge for any use (Neumann, 2024). From a technical perspective, the goal is being driven forward in particular by the GDI-DE project, which is accompanied by strategic concepts (*Nationale Geoinformationsstrategie*, NGIS) and task forces (cf. Weke et al., 2024b, 2024a).
Since the second amendment of July 13, 2017, to the German law on open government data/*E-Government-Gesetz* (EGovG), which regulates the handling of data by federal authorities, requirements for open data can be found in § 12a. According to this, federal authorities are obliged to publish raw data immediately after collection, in a machine-readable format, with metadata, free of charge, without mandatory registration and without justification. However, with regard to geodata most of the cases are already covered by the GeoZG (Neumann, 2024).
In 2019, Directive 2003/98/EC on the re-use of public sector information (PSI) was revised and renamed the Open Data Directive (2019/1024/EU, "Directive on open data and the re-use of public sector information") (Neumann, 2024). The German law on the use of public sector data / *Datennutzungsgesetz* (DNG) of July 2021 implements these EU directives. Public authorities, public companies in the water, transport, and energy supply sectors, and certain research institutions should therefore make data that falls within the scope of the DNG openly available by default. The application of this data for both, commercial and non-commercial use is possible.
The Open Data Directive was supplemented by the Commission Implementing Regulation 2023/138/EU of December 21, 2022, which es-

tablishes a list of so-called "high value datasets" and the modalities for their publication and re-use. Public bodies or public enterprises must make this data available free of charge, under an open license and in a machine-readable format. The most important exceptions[5] are personal data and data whose publication could jeopardize public safety. Following the implementing regulation, numerous new open geodata sets were provided in June 2024, which was a significant progress for work involving open geodata. Many of the data published because of the regulation is available at geodata portals of the federal states (cf. table 3.4 in section 3.4).

2.2. Potentials of openness

Open data and open source applications drive value for society in many ways. This benefit can be classified from various perspectives – economy, civil society, administration, and science – based on its impact. In his dissertation on open data Paderta (2012) describes four levels of argumentation for open (governmental) data, which can in parts also be applied to open software in a slightly modified form.

The **formal argument** states that data financed or collected with public funds, or software developed or commissioned with public funds, must in principle be open, as it "belongs" to the taxpayer. This argument is implemented as a guiding principle in laws such as the German freedom of information act/*Informationsfreiheitsgesetz* (IFG) and the German law on environmental information/*Umweltinformationsgesetz* (UIG). According to the law everyone has a right to access official information from federal authorities, regardless of how it is stored (§§ 1 and 2 IFG, § 3 UIG). Other European and German legislations of recent years contain comparable rights (cf. section 2.1.3). In terms of software this argument is often subsumed as "public money – public code" (Albers et al., n.d.).

The **democratic argument** describes open data as the basis for citizens to form their own opinions. Only through access to information

[5] List of exceptions in Article 1 of 2019/1024/EU

they can freely decide or participate in decision-making processes. Open data also increases the transparency of political decisions by making the underlying facts visible and the arguments derived from these facts comprehensible (cf. preamble in the Open Data Charter (ODC), 2015). This helps to build trust in government agencies and their functioning. Open data foster stakeholders' decision-making ability and mutual understanding in conflicts of interest. They reveal the framework conditions and interests of various decision-makers. Applied to software, the argument can be interpreted as a *trustworthiness argument*. Due to the availability of the source code, the reliability of software can be assessed and errors/bugs or potential threats can be reported[6].

The **economic argument** for open source software and open data is based on more efficient and cost-effective public sector operations (cf. BMI, 2021). If data is openly accessible, it does not need to be stored, maintained, or even collected by multiple entities. Publishing data is also often an opportunity to check its quality. It can be reused by other actors for other purposes (cf. Bennett & Harvey, 2009). A decisive prerequisite is the usage of metadata to describe the published content and open standards (cf. article 4 of regulation 2024/903/EU). Open Standards in this context are "internationally recognized specifications that let different systems exchange information seamlessly" (OGC, 2024). They can be assessed and implemented without any dependencies on non-open software or data (FSFE, n.d.). Open standards are used for metadata, e.g. XML, RDF or Dublin Core (Bennett & Harvey, 2009) as well as for the data or application itself. The Open Geospatial Consortium (OGC) develops a wide range of standards used in for GIS applications that follow the provisions of the international geodata standard ISO 19111:2019. Among these are standards for general geospatial data models and storage (e.g. Simple Features Access, geography markup language (GML), OGC GeoTIFF, keyhole markup language (KML)), OGC application programming interfaces (APIs) as well as data models for specific domains (e.g. OGC WaterML, CityGML), web services (e.g. WMS, WFS), sensors, catalog services and "containers" for geo-

[6] A common quote in this context is *Linus' law* by Eric Raymond stating "given enough eyeballs, all bugs are shallow" (cf. Haklay et al., 2010)

data such as Geopackage and netCDF (OGC, 2024). In the field of wastewater infrastructure, the XML-based ISYBAU format was implemented for the collection and loss-free exchange of wastewater-related information between the clients (building authority) and contractors (engineering office, inspector). In the field of land-use planning and constructional planning, XML-based geodata standards such as XPlanung or XBau have been developed to simplify data exchange (XLeitstelle, 2020). Such specifications are essential to enable interoperability as required by the FAIR principles. The same applies to open source software projects. Once a program has been created, it can be used elsewhere, even in parts, or adapted to the needs of other users without the costs of completely redeveloping it. Open software also makes administrations more independent and ultimately more cost-efficient, as they are not tied to a specific developer or service provider and their cost expectations. Using open standards and interfaces also makes it easier to switch to other software with the same standards and interfaces.

The **innovation argument** focuses on the potential of open data to promote the development of novel applications or to reveal gaps in research in the first place. More accessible data enables to carry out more comprehensive and detailed analyses, e.g. by artificial intelligence (AI) applications (cf. Agarwal et al., 2023; Lowe et al., 2022; Seshan et al., 2023). By using open licenses data sets that would otherwise only be available to a limited group of users can be combined, compared, or incorporated in new fields of research. Due to technological developments in recent decades and the availability of digital devices, there is an ever-increasing amount of data in today's world. Much of this data has a spatial reference, whether in the form of spatial metadata such as the location where a photo was taken or by the actual purpose of the data (digital maps and plans, GPS tracks, remote sensing data). They are produced and made available by a large variety institutions or individuals (cf. numbers 8 to 12 in the preamble of the PSI directive 2019/1024/EU). Official data is collected, produced and published in the context of administrative procedures (e.g. land development plans, census). Voluntary communities collect and share geodata as so-called “volunteered geographic information” (see also 4.1.1). Scientific institutions collect and publish spatially referenced data as part of their research activities. The exchange with other research institutions, reuse in other research projects, or reuse in meta-studies are not just a side effect but an important part of scientific publishing.

A position paper by the German national/federal state working group on water/*Bund/Länder-Arbeitsgemeinschaft Wasser* (LAWA) on dealing with conflicting goals in adapting to the effects of climate change points out that, in addition to the availability of the data itself, knowledge about the availability of existing information is also a decisive factor (LAWA, 2023). From a business perspective, open data, especially open geodata, can be used to develop new business models. The German open data strategy (BMI, 2021) mentions open data as a key factor for economic growth and for fostering Germany’s attractiveness as a business location, especially for start-ups and small or medium-sizes enterprises.

Successful open source projects are often supported by an active community in which, in the best case, the users are also the developers. A major potential here lies in the ability to analyze and improve existing program code with constant feedback from the practitioners view. Additionally, by investigating and understanding open software and the program code behind it, a learning process can be observed, both on an individual as well on a community level. This, in turn, enables contributions to software development by identifying potential enhancements, workarounds and bug fixes. By mentioned processes, the community can establish a “culture of critical evaluations and peer learning” (Bonvoisin et al., 2017). This effect within open source projects could be attributed to both the economic and the innovation argument.

3. Applicability in the context of water management

The advantages of open source and open data of 2.2 are outlined without any specific context. In order to evaluate their potentials and obstacles in the context of water management, it is at first necessary to outline this field of application in detail (section 3.1) and highlight specific challenges (section 3.2). Subsequently, two central digital tools for water management planning are presented, in whose development open source applications have played an important role: geographic information systems GIS and models (section 3.4). Figure 3.1 illustrates the structure of the chapter.

3.1. Objectives, fields of action and stakeholders

According to DIN 4049-1, water management is defined as the " target-oriented regulation of all human impacts on surface water and groundwater" (*"Zielbewusste Ordnung aller menschlichen Einwirkungen auf das ober- und unterirdische Wasser"*). On the one hand, this definition emphasizes the orientation of water management activities towards strategic objectives that are determined by climatic, demographic, political, and, above all, legal conditions (Arle et al., 2017). These objectives, specified by the political and legal framework, are described in section 3.1.1. On the other hand, the aforementioned definition states that water management not only aims to use water as efficiently and economically as possible, but also fulfills a coordinating function that takes into account all human impacts on water resources, and, where necessary, prioritizes or balances them against each other. Human activities affecting water resources cannot be attributed solely to the typical

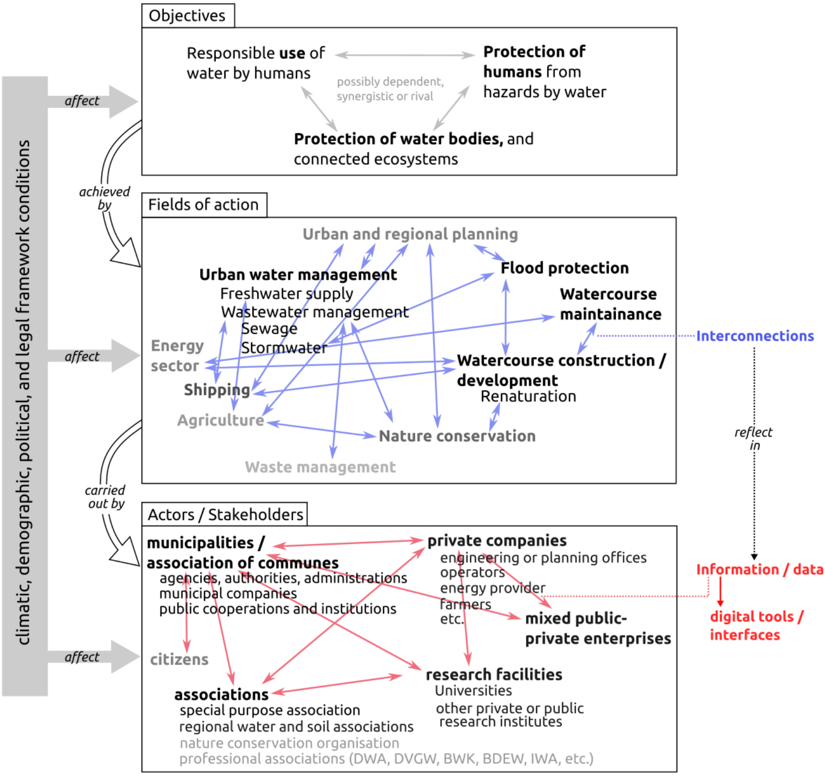


Figure 3.1.: Objectives (section 3.1.1) in water management define the diverse and interconnected tasks and fields of action (section 3.1.2). Accordingly, the activities of the water management stakeholders involved (section 3.1.3) are characterized by a constant exchange of information between various sectors, possibly each with sector-specific standards regarding information or data. Each of the three “layers” is affected or influenced by the framework conditions

areas of water management (urban water management, water protection, flood protection, etc.). The activities of other sectors, such as spatial planning, agriculture or forestry, are closely linked to those of water management through interdependencies. This aspect is explained in section 3.1.2. As a result, numerous stakeholders are involved in water management, in the public sector at various administrative levels as well as in the private sector. Section 3.1.3 provides an overview of this diversity of stakeholders and presents two key groups in Mecklenburg-Western Pomerania as examples.

3.1.1. Objectives

The legal framework for water management spans various administrative levels and has varying degrees of binding force. International targets are set out in the United Nations' 17 Sustainable Development Goals (SDG). For example, Goal 6 (Clean Water and Sanitation) covers access to sanitation and clean drinking water, the efficient and sustainable use of water, and the protection of natural water bodies from pollution. SDG number 14 ("Life below water"), specifies various protection targets for oceans and their ecosystems (Alcamo, 2019). Although the SDGs are not legally binding, they serve as guidelines for political actors who set specific requirements for water management through treaties, action programs, regulations, and laws.
Requirements for water management at EU level arise, for example, from the EU Water Framework Directive (WFD) (2000/60/EC), the Directive on the Assessment and Management of Flood Risks (2007/60/EC), the Drinking Water Directive (2020/2184/EU), the Regulation on Minimum Requirements for Water Reuse (2020/741/EU) , or the Directive on urban waste water treatment (2024/3019/EU). Because unlike regulations, directives in the context of European law are not directly binding, they have to be implemented in national legal systems in the form of laws and national regulations. In Germany, these include for example the federal water law/ *Wasserhaushaltsgesetz* (WHG), the groundwater regulation/ *Grundwasserverordnung* (GrwV), as well as regulations for potable water/ *Trinkwasserverordnung* (TrwV), and

surface waters/*Oberflächengewässerverordnung* (OGewV). At the state level, state laws and regulations (e.g., the water law/*Landeswassergesetz* (LWaG) or the regulation on communal wastewater / *Kommunalabwasserverordnung* (KAbwVO M-V) of the state of Mecklenburg-Western Pomerania) specify the law applicable nationwide.
Standards and technical regulations developed by professional associations (DIN, DWA, DVGW, BWK, etc.) also shape water management objectives, for example in the form of limit values, benchmarks or target values for water management. In addition to the documents mentioned above, a number of concept papers and strategy papers also set out objectives for water management at various organizational and spatial levels. Examples include the German national water strategy /*Nationale Wasserstrategie* with the Water Action Program /*Aktionsprogramm Wasser*, the national moorland protection strategy /*Nationale Moorschutzstrategie*, and the national strategy on biological diversity /*Nationale Strategie zur Biologischen Vielfalt* (Mehl & Iwanowski, 2023).
The objectives specified by the legal framework as described can be roughly divided into three sub-areas, namely

1. the protection of water bodies/water, etc. from human influence. This can be found, for example, in § 1 WHG, which stipulates the protection of water as a component of the natural environment and as a habitat for animals and plants (*"Wasser als Bestandteil des Naturhaushalts [. . .] [und] als Lebensraum für Tiere und Pflanzen"*).

2. protection of humans from hazards by water. This objective includes, for example, protection against flooding [1] as well as the safe drainage of residential areas (collection, transport, and treatment of sewage and rainwater)

[1] Defined by § 72 WHG as temporary overflow of land which is not normally covered by water, in particular by surface water or seawater entering coastal areas. This does not include flooding from sewage systems. (*"zeitlich beschränkte Überschwemmung von normalerweise nicht mit Wasser bedecktem Land, insbesondere durch oberirdische Gewässer oder durch in Küstengebiete eindringendes Meerwasser. Davon ausgenommen sind Überschwemmungen aus Abwasseranlagen."*)

3. responsible use of water by humans and securing water resources, for example for the supply of potable water and water for industrial use.

3.1.2. Fields of action

The central fields of action in water management include urban water management with the sub-sectors of water supply (water collection, purification and distribution) and wastewater disposal (sewage systems, retention and treatment), watercourse maintenance, watercourse development measures, and the operation of facilities and infrastructure for various uses (shipping, fishing, hydropower, etc.). River management is targeted to reconcile long-term protection of water bodies and related ecosystems as well as the maintenance of infrastructures and the interests of various stakeholders in using the rivers' ecosystem services (Chatrabhuj et al., 2024; Tickner et al., 2017). In this context, it must deal with impacts from past events (e.g. drought or flooding), existing structural alterations (e.g. dams, river beds) and be prepared for future changes, where possible. Thus, river management usually includes both, reactive and proactive measures and strategies (Palmer et al., 2009).

In addition, there are numerous other fields of action that are not traditionally associated with water management but are intrinsically tied to the aforementioned objectives and tasks.

The water requirements for irrigation, drainage of farmlands, and diffuse substance inputs in the form of nutrients and pesticides into water bodies from farmland or grassland inevitably link agriculture with water management issues. Accordingly, cross-references between the two sectors can be found both in rules and standards for water management such as the WFD (Mehl & Iwanowski, 2023) and in those related to agriculture. For example, the water management sector's objective of increasing nutrient retention by means of riparian strips and restricting the use of fertilizers in catchment areas of eutrophicated rives is also noted in agricultural regulations (e.g., the German fertilizer ordinance/*Düngemittelverordnung* (DüMV), or the European Nitrates Directive (91/676/EEC)). In order to improve water quality in standing

water bodies, rivers or groundwater, an objective “trilogue” between water management, agriculture, and politics is necessary.
Similarly, functional links between urban and regional planning and water management tasks can be found (Fletcher et al., 2013). Most obviously, the development of new settlement areas involves the construction of drainage infrastructure for wastewater and rainwater. The development of previously natural areas also increases surface sealing, thereby increasing surface runoff after precipitation events at the expense the other components of the water balance, evaporation and infiltration. This interference with the water balance is not only noticeable in the urban climate, but also in the coaction between the drainage infrastructure and the receiving water bodies (Mehl et al., 2015). Based on the recognition that negative effects on receiving waters have been observed in the past in terms of both drainage regimes and water quality, there has been a rethinking in urban drainage planning. Therefore, modern technical regulations and their updates are increasingly aimed at reconciling the two objectives, safe drainage as well as water protection, and setting priorities for measures in the case of potential conflicts of interest (e.g. DWA-A 100, DWA-A/M 102). Similarly, issues relating to nature conservation and species protection in the energy sector and waste management are linked to the remit of water management. The interaction between the different fields of action and remits make river management a cross-sectional tasks across different technical disciplines and administrative levels. Accordingly, a wide range of stakeholders is involved in water management.

3.1.3. Stakeholders

Since urban water management fulfills public services, municipal authorities or utilities (municipal or city-owned corporations, special-purpose associations) are primarily responsible in operations, but also private companies for drinking water supply and wastewater (Arle et al., 2017; Watson, 2004). Among these entities, there is a wide variety of organizational forms (Arle et al., 2017). Depending on the number of

inhabitants which are supplied[2] by a facility these might be considered operators of critical infrastructure according to European an German law (cf. Directive 2022/2557/EU, German draft law for strengthening the physical resilience of operators of critical facilities/*Regierungsenwurf z. KRITIS-Dachgesetz*, German law on the federal office for information security/*BSI-Gesetz* (BSIG) as well as § 3 of the connected regulation *BSI-Kritisverordnung* (BSI-KritisV)). In data collection, planning, and development, private companies (engineering and planning offices, laboratories) are often involved, as are some research institutions (universities, state institutes). Public authorities cover a wide range of water management activities, from planning and approval to the supervision of water management facilities and monitoring tasks. Unfortunately, there are usually separate administrative competences for "blue" and "green" and "grey" infrastructure, population, nature and environmental protection, each with their own interests and perspectives (Fliervoet et al., 2015). In addition, there are spatially separate responsibilities, e.g. for watercourses which extend across national borders, several federal states, municipalities or public authorities (Arvidsson et al., 2022; Jalink & Dieperink, 2024; Lorenz et al., 2001). Using M-V as an example, two groups of stakeholders will be described in particular below.
In 2021, there were 108 entities for wastewater in M-V of which 69 % were municipal and 31 % were associations ("*Abwasserzweckverbände*", WBV). Due to the generally low population density and its concentration in larger cities, there are numerous small wastewater treatment plants in rural areas, which, however, only treat a small portion of the state's communal wastewater. Nearly 84 % is treated by the few larger wastewater treatment plants (over 10000 PE) which cover the larger cities and their surrounding areas (LUNG, 2023). Here, in many cases entities are responsible for both drinking water supply and wastewater disposal. For example, the Warnow Water and Wastewater Association/*Warnow-Wasser- und Abwasserverband* (WWAV), founded in 1994, is responsible for drinking water supply and wastewater dis-

[2] drinking water supply of more than $22 \times 10^6\,\mathrm{m}^3\,\mathrm{year}^{-1}$ or wastewater disposal for more than 500000 inhabitants or population equivalents (PE) according to annex 2 of BSI-KritisV

posal in the urban and suburban areas of Rostock [3]. The association is organized as a public corporation whose members are the city of Rostock, as well as the Water and Wastewater Association Rostock-Land, to which 28 surrounding municipalities belong (WWAV, 2025). The operation and maintenance of the facilities, as well as the collection of contributions, is carried out by Nordwasser GmbH, whose shareholders are by 49 % the WWAV itself and by 51 % Rostocker Versorgungs- und Verkehrsholding GmbH (Nordwasser GmbH, 2025). As drinking water networks, waterworks, sewage networks etc. are critical infrastructure, the corresponding geodata are not made publicly, “open” available by the such companies (DWA, 2020a; Holländer et al., 2020). Likewise, data in a high spatial resolution, e.g. on water consumption which could be attributed to single households or companies are protected for reasons of privacy or company secrecy (cf. Arvidsson et al., 2022). Available data are summarized values regarding the overall consumption of water, the effectiveness of wastewater treatment plant (WWTP), or the total amount of people supplied. At the same time, such data is needed for many scientific issues. Therefore, alternative approaches for generating this data have been developed. On example which was developed within this thesis is described in section 4.1.
The federal state’s 27 regional associations for watercourses and soils / *Wasser- und Bodenverbände* (WBV) are responsible for watercourse maintenance[4] on second-order watercourses[5] (§ 1 of the Law on the Formation of Waterway Maintenance Associations/*Gesetz über die Bildung von Gewässerunterhaltungsverbänden* (GUVG)). They are public-law corporations with the right to self-administration, whose members are primarily the municipalities in the respective association area. The main task of the WBV is to ensure proper drainage and floodwater discharge (§ 73 state law on water ressources/*Landeswassergesetz M-V* (LWaG)). This also includes “the maintenance and operation of

[3] The area of responsibility (figure 4.1), key metrics and a description of wastewater quantities in section 4.1.2

[4] Definition of “watercourse maintenance”/*Gewässerunterhaltung* according to § 39 WHG

[5] Definition of “second-order watercourses”/*Gewässer 2. Ordnung* according to § 48 LWaG

facilities used for water drainage" (§ 62 LWaG). The associations located on the coast are also responsible for the maintenance of dykes for the protection of agricultural land (§ 83 (3) LWaG).
In addition, the associations can voluntarily take on further tasks (cf. § 4 German law on the formation of waterway maintenance associations/*Gesetz über die Bildung von Gewässerunterhaltungsverbänden* (GUGV), § 2 Water Associations Law/*Wasserverbandsgesetz* (WVG)). This is particularly the case in the areas of waterway development[6], renaturation, and moorland protection. As experts on the rivers in their area of responsibility, the WBV also issue advisory opinions on projects by other authorities or agencies, e.g., when granting water law permits for discharge and withdrawal.
For their tasks the WBV collect geodata regarding rivers and associated water infrastructures (e.g. weirs, dams, pipes). Large parts of the data are published in a data portal by the state authority for environment protection / *Landesamt für Umwelt, Naturschutz und Geologie Mecklenburg-Vorpommern* (LUNG) and is therefore openly available (LUNG, n.d.-a).

3.2. Challenges

As in other specialist areas, digitization in water management often represents an additional task that must be completed alongside the "daily business". In order to meet these demands, both the current workforce must be trained and new employees hired. However, due to socio-demographic changes recruiting new personnel can be challenging, in particular in rural areas. (cf. Mehl & Iwanowski, 2023). In addition, there are specific challenges in water management, which are illustrated in this chapter through a comprehensive review of scientific literature. The drivers for the challenges presented here cover conflicting uses of water ressources, land use changes and impacts of climate change. In this context, particular attention is paid to links and (inter-)dependencies between the challenges and associated processes. Sec-

[6] Definition "waterway development"/*Gewässerausbau* according to § 76 German water resources law/*Wasserhaushaltsgesetz* (WHG)

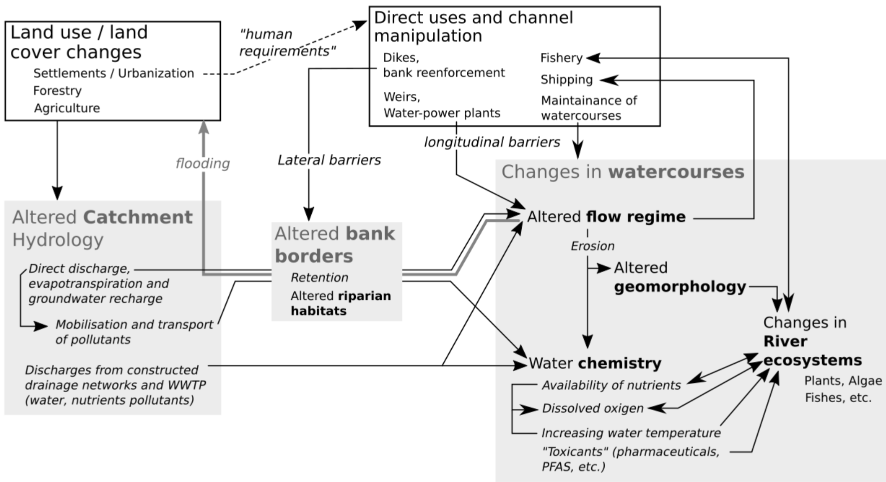


Figure 3.2.: Example of impact chains through human activity on river ecosystems; italic text and arrows: effects or impacts; bold text: affected locations; Basic ideas of the figure were adjusted from Fletcher et al. (2013) and Wenger et al. (2009)

tion 3.2.1 focuses on river management, based on the third publication (Schilling et al., 2025a) of this cumulative thesis. The sections 3.2.2 and 3.2.3 also build on this publication, but are expanded by aspects of water management in residential areas.

Various approaches can be found in scientific papers on water management or water ecosystems that describe and explain the dependencies mentioned above. For example, with regard to critical infrastructure, Arvidsson et al. (2022) refer to interdependencies as “a relationship when two infrastructures are dependent on each other, either directly or through feedback-loops”. Interactions in urban hydrology can be “both physical and in terms of management” (Fletcher et al., 2013). Possible impact chains within catchments and river channels through physical changes by urbanization processes are depicted in figure 3.2. Franklin et al. (2024) distinguish between structural (continuity of the physical environment) and functional (species-specific strategies and behavior) "connectivity" in aquatic ecosystems. Heasley et al. (2019), analysed dependencies between the characteristics of rivers and riparian zones (flow type, sediment size, habitat quality and modification) and network topology. Mehl and Iwanowski (2023) refer to a functional interconnection ("*funktionale Verzahnung*") of different landscape components in which positive feedback and synergies exist. The study of Vrebos et al. (2017) investigated spatial patterns resulting from multi-directional and unidirectional processes in a catchment in Northern Belgium. A common feature of the mentioned papers is that functional connections and dependencies are explained by spatial aspects (e.g. topology, flow paths, patterns, proximity) at different scales, which underlines the need for suitable geodata and digital tools (section 3.4).

3.2.1. Competing interests of use and protection goals in river management

Rivers and streams are used by humans in a many different ways. As part of man-made infrastructure, they are utilized to transport goods, supply energy, or as a receiving watercourse for wastewater and stormwater. Rivers provide water for domestic, agricultural or industrial use or serve as recreational areas. Such benefits for humans are usually referred to as "ecosystem services" (Karki et al., 2020). Among the variety, different claims or types of ecosystem services can be in competition with each other. This challenge is illustrated by Tickner et al. (2017). Their paper shows how physical infrastructures and formal or informal institutions affect the availability of ecosystem services for different groups in society. For example, protecting rivers as water resources for drinking water against irrigation demands in agriculture has been of great interest worldwide for years. Where and when withdrawals can take place, for what purpose and in what quantity, must be coordinated by river management as part of a general water governance (Engle & Lemos, 2010). Constraints can be implemented by means of water rights or water protection zones (Palmer et al., 2009). German rules and standards, for example envisage a division into protection

zones, using spatial buffers and catchment areas (Walcher & Bormann, 2015).
Conflicts in which the use of one river ecosystem service precludes another use contain an obvious spatial component. Due to the hierarchical nature of river networks, there is a clear differentiation between what is upstream and downstream of a given point in a river (Heasley et al., 2019; Thoms et al., 2018). The dependency results from the flow path of the water. For example, the extraction of water or the building of dams and storage has an influence on the possibilities for water extraction in downstream river reaches (Palmer et al., 2009). A similar problem is a scenario in which a preventive measure threatens to have adverse effects elsewhere (Arvidsson et al., 2022; Serra-Llobet et al., 2022), or when measures have to be prioritized. For example, Singh et al. (2023) identified critical river catchments for based on morphometric parameters (see section 3.4.1) and land use information to optimize measures against erosion.
The use of rivers and streams by humans is also one of the most important stressors for their ecosystems (Lorenz et al., 2001). Man-made structures in rivers' cross sections and embankments have serious impacts on lateral and longitudinal connectivity, and water level and flow. For instance, dykes along rivers are an important element of flood protection for adjacent areas, but at the same time they interrupt lateral connections between ecosystems. Dams built for water retention or hydropower generation in river valleys significantly alter the flow regime and disrupt longitudinal reachability for fish and other migratory species (Franklin et al., 2024; Grabowski et al., 2022). Modified flow regimes downstream of hydropower plants also affect macrophytes, macroalgae, diatoms and macroinvertebrates (Rivaes et al., 2022). Further impacts of physical barriers, abstractions and discharges have been reported in terms of hydromorphology and natural sediment transport (Palmer et al., 2009).
A major challenge in terms of water quality is eutrophication caused by anthropogenic inputs of nutrients. Emissions originate mainly from point discharges (wastewater and industrial facilities) in urban areas and diffuse pollution from agriculture in rural areas (Mockler et al.,

2017; Sliva & Williams, 2001). In natural rivers, adjacent riparian areas and floodplains along can act as sinks, whereas in other sections pollutants are mainly transported along the flow path. These functional dependencies of different areas within a catchment (e.g. material exchange processes) are often only recognized by their cartographic representation. A spatial assessment of emission points and flow paths on a watershed scale is therefore crucial in water quality management to identify sources and endangered ecosystems downstream (Köhler et al., 2024; Kourgialas et al., 2024).

3.2.2. Challenges caused by land use and land cover change

The ongoing use of land as a resource for agriculture and settlement areas and thus the loss of natural areas can be observed worldwide. As a change in land use generally also causes a change in land cover, i.e. the physical and biological nature of the land surface (change in vegetation, sealing through development, soil compaction), land use and land cover (LULC) changes are usually regarded as a single phenomenon. Such interventions are noticeable in all components of the water balance (Grabowski et al., 2022). Conversion of forest land to agricultural land and sealing of soils by urbanization processes are particularly relevant. Sealed settlement or traffic areas lead to increased runoff rates and, lower infiltration and baseflow (Fletcher et al., 2013). Compared to forest areas, agricultural land tends to be characterized by reduced evaporation, and lower water retention through interception and infiltration (Leta et al., 2021). The sealing of surfaces reduces groundwater recharge and increases total and peak run-off after precipitation events and higher soil erosion (Panagos et al., 2015). In rivers, these long-term changes become noticeable as gradual changes of the flow regime (Guse et al., 2015). Changes in land use therefore have a significant impact on flood risk (Kachholz et al., 2021). Land use changes within a catchment are also closely related to a variety of water quality parameters (Vrebos et al., 2017).

The mentioned effects of land uses changes on river processes can be observed regardless of proximity to the river (Grabowski et al., 2022).

Consequently, impact assessments of LULC change are typically based the share of a specific land use or the degree of sealing within (sub-)catchments as the primary indicator. The indicator is calculated by a spatial overlay of land use information and catchment areas (Guse et al., 2015; Kachholz et al., 2021). Altered flows in rivers also affect the geomorphology, adjacent vegetation and the availability of ecosystem services on various spatial scales. In order to describe the interactions between rivers and adjacent areas Grabowski et al. (2022) introduce the term “land-river interface”. The core of the concept is the delineation of four zones (hydraulic active zone, geomorphic active zone, surface water connected zone, and soil moisture zone), each of which is characterized by specific processes.
Comparable effects also occur in urban areas in the interaction between the sewer network and the connected catchment area. The increasing level of surface sealing is also a considerable driver of temporary surcharge of the drainage infrastructure (Stokman et al., 2015). Similarly, certain land use categories can be correlated with the probability of higher pollution levels in urban storm water discharges. These effects are taken into account, for example, in the German DWA working paper series A/M 102. According to the regulation, construction projects must not significantly alter the components of the natural water balance compared to the undeveloped reference state in the long-term average. However, the implementation of appropriate measures requires a detailed land use analysis, for which the relevant geodata must be available (Schneider et al., 2022).

3.2.3. Climate-related challenges

Man-made climate change is measurable worldwide in the form of rising temperatures and this trend is likely to continue in the future. Depending on current and future emission scenarios, the average air temperature is projected to increase by 1.5 – 4 °C until the end of the 21st century The consequences of climate change are particularly visible in the processes of the water cycle and their dynamics. Warmer air temperatures primarily lead to increased evaporation and can thus lead to

temporary drought. Increasing evaporation and air temperatures also promote the occurrence of heavy rainfall due to a higher atmospheric water availability (IPCC, 2023).
Regional climate development fits into the backdrop of global climate change as described in the regular reports of the Intergovernmental Panel on Climate Change (IPCC). For Mecklenburg-Western Pomerania, regional climate forecasts have been drawn up by the German meteorological service/*Deutscher Wetterdienst* (DWD), which shows a spatially differentiated picture within the state. In general, sea levels are expected to rise, primarily affecting the country's coastal areas. However, depending on the gradient of coastal rivers, inland water bodies may also be indirectly affected by backwater. Climate change is already noticeable nationwide in temperature and precipitation patterns. Generally rising temperatures increase potential evaporation and, with sufficient water availability, actual evaporation as well. No clear trend can be identified in the average annual precipitation figures. However, both types of temporary extremes, heavy rainfall and prolonged periods of drought, are increasing in frequency and intensity (DWD, 2018). This has a significant impact on the local water balance.
Droughts and heavy rainfall events change the flow regimes of rivers, water temperatures and the average water availability, with significant effects on aquatic ecosystems (Mehl & Iwanowski, 2023; Tonkin et al., 2019). They physically influence the structure of habitats, the transport or deposition of sediment (Nones, 2020) and organic matter, as well as biodiversity and the stability of habitat structures (Rivaes et al., 2022). Increased water temperatures and longer water residence times at low water levels in flowing waters change the framework conditions for biochemical processes, e.g. the pH value or the solubility of substances, and promote algae growth that is harmful to other organisms (Köhler et al., 2024).
From an anthropocentric perspective, there are two types of climate-related challenges. Firstly, climate change exacerbates existing use-related problems in rivers mentioned in section 3.2.1 or creates conflicts of use in the first place (cf. LAWA, 2023). This challenge mainly arises from negative impacts on river ecosystem services. For example, with

rising temperatures, there is a an increasing demand for water for agricultural irrigation and public water supply. And the increasing demand intensifies the competition for water resources described above. At the same time water withdrawals from rivers must be limited in order to ensure minimum water levels or flows to maintain the ecological status of reaches (Tonkin et al., 2019). Again, the topology of the river network results in a dependency on measures located upstream, underlining the need for a spatial impact assessment. Adapting river management to climate change must consider the functional interdependencies between infrastructure and ecosystems, as well as causal chains in aquatic and terrestrial habitats at the watershed scale (Palmer et al., 2009).

Secondly, as a result of climate change, watercourses themselves increasingly pose risks, for example due to flooding after heavy rainfall events (Fernandez et al., 2015; Rahman & Di, 2017). In common definitions, “risk” refers to the combination of a hazard and the associated damage potential. A “hazard” represents an event with a certain extent, evaluated with its probability of occurrence. Hazard assessment is therefore primarily based on a time-related classification of events, which is achieved by looking into the past: the probability or recurrence intervals of heavy rainfalls or droughts of a certain duration or intensity are determined using measured time series. However, this type of risk assessment is increasingly associated with uncertainties in the context of long-term changing climatic conditions, a problem which is called “shifting baselines”. A spatial approach for assessment of flood hazards can help to cope with these uncertainties, because the hydrologic response to precipitation inputs depends on the spatial arrangement of soil properties, river channels and confluences. Spatial metrics of river network structures have been described, for example, by Heasley et al. (2019), including drainage density, stream orders and elevation properties. Examples of corresponding GIS analyses can be found in section 3.4.1 of this paper.

Heavy rainfall events, combined with the surface sealing (cf. section 3.2.2), are also posing an increasing threat in urban catchment areas. Historically, stormwater infrastructure was designed to collect and quickly drain discharges from the city through underground sewers into

receiving waters. Despite strong competition for space in urban areas, decentralized retention areas must be created to avoid the dangers posed by uncontrolled surface runoff in case of surcharges (Stokman et al., 2015). Especially in coastal regions, with rising sea levels the coincidence of storm tides and intense rainfall events pose an increasing threat to residential areas (Bormann et al., 2024).
The damage potential of an event can be differentiated into the factors "exposure" and "vulnerability" (IPCC, 2023; O'Neill et al., 2016; Rahman & Di, 2017; Ziegelaar & Kuleshov, 2022). This classification risk into the factors hazard, exposure and vulnerability is also referred to as the "risk triangle" in various publications (e.g. O'Neill et al., 2016; Ziegelaar & Kuleshov, 2022). "Exposure" stands for the number of people, the size of ecosystems and the quantity or value of goods that would be affected by the event. The "vulnerability" summarizes the extent to which affected people, ecosystems and goods do or do not have protective mechanisms and coping strategies.

3.3. "Openness" in integrated water management

The various interdependencies between the mentioned challenges and fields of action call for holistic water management concepts which include the protection of humans, protection and planning or operation of water-related infrastructure at once. Such concepts have been developed and discussed in various publications with terms like "Integrated Water Resource Management" (IWRM) or "Integrated River Basin Management" (IRBM) (Sörensen et al., 2016; Tickner et al., 2017; Watson, 2004). In the context of urban water management similar concepts such as integrated urban water management (IUWM), green infrastructure (GI), water sensitive urban design (WSUD) or low impact development (LID) are applied, linking urban planning and water related issues (Fletcher et al., 2013; Fletcher et al., 2015). Guidelines for integrated urban water management in Germany are provided by the technical regulation DWA-A 100. With a focus on flood protection in urban areas, an integrated approach was applied, for example, to the hydrological risk analysis in the "Integrated Drainage Concept"/*Integriertes*

Entwässerungskonzept (INTEK) of the Hanseatic and University City of Rostock. The concept evaluates the runoff during extreme precipitation, the capacity of the sewer network, receiving waters, and pumping stations, the risk posed by above-ground runoff channels and low-lying areas, as well as high groundwater levels and flooding due to storm surges from the Baltic Sea, given the special location conditions. By combining these aspects that were initially considered individually, an overall assessment of the hydrological risk is obtained (Mehl et al., 2015).
In the context of river management, applying integrated approaches seems to be obvious, given the evident functional interconnection between catchment hydrology and watercourse. The integrated view on river management is reflected, for example, in the WFD, through management by international river basin districts and cross-references to agriculture (Art. 10 (2) WFD). In most cases, anthropogenic influences from water use, artificial structures and land use or land cover changes in catchments are the main source of negative impacts on rivers (Acreman, 1996; Grabowski et al., 2022; Köhler et al., 2024; Rivaes et al., 2022; Tickner et al., 2017). There are very few rivers in the world that have not been impaired by human influence (Vörösmarty et al., 2010). However, there is usually not a single cause, but a combination of drivers related to human activities and development, climate change and "inherent problems" such as geological aspects and the spatial structure of catchments (Heasley et al., 2019; Karki et al., 2020). The diversity and interdependence of such processes and factors requires highly interdisciplinary approaches (Arvidsson et al., 2022; Tickner et al., 2017; Warmink et al., 2017). Due to the amount and diversity of stakeholders involved, possibly at different administrative levels (cf. section 3.1.3), governance concepts are needed which foster cooperation or even better, collaboration (Jalink & Dieperink, 2024; Watson, 2004). For example, Tickner et al. (2017) provide a framework for river management research, policy and planning that integrates assessing impacts and benefits of infrastructure and ecosystem services for different societal groups in different locations. Warmink et al. (2017) develop adaptive strategies for policymakers to overcome the uncertainty of long-term changes in river management.

Such integrated water management approaches require a high degree of communication between stakeholders, and thus the mutual provision, exchange and merging of (spatial) information and data (LAWA, 2023; Lorenz et al., 2001). Sharing information is, for example included in the 10 design principles for integrated drought risk governance suggested by Jalink and Dieperink (2024). Besides the data itself interfaces and digital tools (section 3.4) to combine this data to create an overall picture are essential in this context. Digital tools for integrated spatial analysis and modeling are, for example, reviewed by Daud et al. (2024), highlighting the benefits of web-GIS for natural hazard management. In order to initiate dialogues among stakeholders, the cartographic representation and spatial topological analysis of protected areas, habitats of endangered species, land use as area information or discharge points can be a good starting point. Examples for the use of of maps and GIS as a communication tool can be found in section 3.4.1.
In the PROSPER-RO project, harmonized geodata sets were created from the raw data of various project partners and merged as the basis for subsequent investigations. These were then made available to participating stakeholders via an internal geodata infrastructure (Hoffmann et al., 2021) based on CKAN (OKF, 2018). In such cooperative projects the actors are both data providers and users. However, one major challenge is that data might be too sensitive for sharing in some cases. Off course, making data accessible must not compromise the security of critical infrastructure under any circumstances (cf. § 8a BSIG). Such concerns have been identified as one major obstacle for cooperative flood management by Sörensen et al. (2016).
Even with these limitations, there are numerous successful examples for the usage of open data for integrated water management concepts. A selection of these will be presented in the following section.

Table 3.1.: Examples of official German geodata portals of federal states and licenses in use. Unless otherwise specified *Datenlizenz Deutschland* refers to version 2.0 of the license and CC refers to version 4.0 of the license

Federal state	Portal / Title	Link	Licenses
Baden-Württemberg	Open GeoData Portal	https://opengeodata.lgl-bw.de	Datenlizenz Deutschland-BY
Bavaria	open bydata	https://open.bydata.de	CC-BY, CC-BY-SA, CC0, Datenlizenz Deutschland-BY, ODbl
Berlin	Geodatensuche Berlin	https://gdi.berlin.de	Datenlizenz Deutschland-Zero
Brandenburg	Geobroker	https://geobroker.geobasis-bb.de/	Datenlizenz Deutschland-BY
Bremen	Geoportal Bremen	https://geoportal.bremen.de/geoportal/	CC-BY
Hamburg	Geoportal Hamburg	https://geoportal-hamburg.de/	Datenlizenz Deutschland-BY, Datenlizenz Deutschland-Zero
Hessen	Geodaten online	https://gds.hessen.de/	Datenlizenz Deutschland-BY, Datenlizenz Deutschland-Zero
Lower Saxony	OpenGeoData.NI	https://ni-lgln-opengeodata.hub.arcgis.com/	CC-BY
Mecklenburg–Western Pomerania	LAiV M-V Downloadportal Geobasisdaten	https://laiv.geodaten-mv.de/afgvk/	Datenlizenz Deutschland-BY

Table 3.1.: Examples of official German geodata portals of federal states and licenses in use. Unless otherwise specified *Datenlizenz Deutschland* refers to version 2.0 of the license and CC refers to version 4.0 of the license (continued)

Federal state	Portal / Title	Link	Licenses
North Rhine-Westphalia	OpenGeodata.NRW	https://www.opengeodata.nrw.de	CC-BY, CC0, Datenlizenz Deutschland-BY, Datenlizenz Deutschland-Zero
Rhineland-Palatinate	Open Data – Freie Daten und Dienste der Vermessungs- und Katasterverwaltung Rheinland-Pfalz	https://lvermgeo.rlp.de/geodaten-geoshop/open-data	Datenlizenz Deutschland-BY
Saarland	Geoportal Saarland	https://geoportal.saarland.de	CC-BY
Saxony	Portal Offene Geodaten	https://geoportal.sachsen.de/portal-offene-geodaten.html	Datenlizenz Deutschland-BY
Saxony-Anhalt	Open Data	https://geodatenportal.sachsen-anhalt.de/gfds/de/gdp-open-data.html	Datenlizenz Deutschland-BY
Schleswig-Holstein	Schleswig-Holstein Downloadportal – Offene Geobasisdaten	https://geodaten.schleswig-holstein.de/gaialight-sh/_apps/dladownload/	CC-BY, Datenlizenz Deutschland-BY
Thuringia	Geoportal Thüringen	https://geoportal.thueringen.de	Datenlizenz Deutschland-BY

3.4. Open spatial data and open source tools in water management

An overview of data portals and licenses in use for every federal state in Germany is provided by table 3.4. Besides these geodata-specific platforms, there are other federal state platforms for open data in general[7], as well as data portals for cities and municipalities. The city of Rostock for example provides geodata in its data platform "OpenData.HRO", mainly with CC0 licenses[8] (HRO, n.d.). Meteorological data for Germany is available to download from the open data server of DWD. The server also offers a variety of climate-related data, e.g. rainfall, air and soil temperatures, solar radiation, atmospheric pressure, etc. in multiple temporal resolutions (DWD, n.d.-c).
In addition to the aforementioned providers, volunteered geographic information (VGI) can be used in water management. Such geodata are are collected and published by a community of volunteers. Data from the OpenStreetMap (OSM) project in particular is used in many applications as an alternative data source, or as a supplement for gaps in official data sets. The data are provided with an ODbl license, e.g. by Geofabrik GmbH (n.d.-a). A detailed description, discussion on data quality and examples of its applications can be found in section 4.1.
The challenges presented above (section 3.2) demonstrate that water management needs software tools to address spatial and / or spatio-temporal links (overlaps, topological dependencies) between water infrastructure, natural watercourses and catchment properties on various scales. Two major groups of applications stand out, which are described below:

1. geographic information system (Subsection 3.4.1) handling spatial data in general and

2. simulation models (Subsection 3.4.2) that can calculate functional (temporal, and physical) components of hydrological and hydraulic

[7] such as https://daten.berlin.de/ in Berlin
[8] As of August 2025, there are 278 data sets, of which 276 are publish with a CC0 license, one with ODbl and one with CC-BY 4.0. (HRO, n.d.)

processes.

3.4.1. GIS-Applications

GIS are digital tools for processing, merging, analyzing and visualizing structured, digital data with a spatial reference ("geodata"). Historically, the term "GIS" comprises hardware, software and associated data or database systems, but it is now often used synonymously for GIS software.
The pioneering era of GIS began in the 1960s with the design of vector and raster data models. Advances in the field of computer science in the 1970s enabled the development of complex data processing algorithms in computerized spatial databases and software for the analysis and visualization of geoinformation. While the GIS innovations of this period mainly took place in scientific institutions and administration, the first commercial GIS began to spread in the 1980s. In 1982, Esri released ARC/INFO, the first version of the ArcGIS product line, which is still the market leader in commercial geographic information software today (Waters, 2018). In the same year, the United States Army Corps of Engineers began developing GRASS GIS, which was initially released as public domain software and later as open source (Neteler et al., 2012). In the 1990s, geographic information science increasingly developed into a scientific discipline. With the increasing use of the internet in the 2000s, web GIS innovations gained in importance (Waters, 2018). This period also saw the start of various open-source GIS such as QGIS and SAGA GIS as well as software libraries such as GDAL/OGR and PROJ (Conrad et al., 2015; Löwe et al., 2022).
Open source applications have become well-established alternatives to commercial GIS products among a wide range of users in recent decades (Conrad et al., 2015; Tebano et al., 2016). Although gaps in documentation, the lack of suitable training material and fewer professional support by companies have been reported as potential drawbacks of open source GIS, there is a trend towards open source in public administration and universities (Coetzee et al., 2020). QGIS in particular enjoys great popularity due to the free availability of software and doc-

umentation, compatibility with numerous data formats and databases, user-friendliness and the availability of tools (QGIS project, 2024). It is distributed with a GPL license (Graser et al., 2025; Lowe, 2010). Additional functionality can be integrated via add-ons or “plugins”. These tools are created by the user community and distributed with publicly accessible repositories, making the software highly customizable compared to proprietary GIS (Löwe et al., 2022; Schilling & Tränckner, 2022). Variations of QGIS are available for different operating systems – currently Windows, macOS, Linux, FreeBSD, OpenBSD, Android and iOS (QGIS project, 2024). The software is developed and maintained by a broad community of users and organisations. For instance, the OSGeo4W distribution is maintained by the Open Source Geospatial Foundation (OSGeo), a non-profit organization dedicated to the development of open-source GIS software and related technology (Graser et al., 2025).

With a focus on the management of natural rivers, three examples of GIS applications in water management are highlighted here. A recurring element of the examples is the use of overlay analyses of different thematic layers. This approach allows the effects of a management measure, such as watercourse maintenance or renaturation, to be mapped in scenarios and initially assessed from the perspective of different stakeholders (agriculture, tourism, flood protection, nature conservation). The identified advantages and disadvantages are then summarized into spatial indicators and combined to form an overall picture (Lorenz et al., 2001). This enables competing objectives to be weighed up and prioritized in a single location or when deciding between different locations.

Identification of flood risks

The spatial assessment of flood risk is based on “mappable” conditions in GIS that influence hazard, exposure and vulnerability (Figure 3.3). Due to the large number of factors, these are often summarized as indicators (Ziegelaar & Kuleshov, 2022). A typical example is the characterization of run-off properties subsequent to a precipitation event, the “hydrological response”, based on the morphology of the water body and catchment area (e.g. in Beven et al., 1988; Diakakis, 2010; Singh et al., 2023; Torrefranca & Otadoy, 2022). These publications consider:

- average and maximum lengths of flow paths calculated using digital elevation models (DEM)
- the size and shape of the catchment
- the “sinuosity” of the river (meandering or straight shape)
- the average gradient in the catchment area and the hypsometric curve
- retention areas such as swales and oxbows
- the number of confluences, strahler order of river parts
- the river network density

For example, the paper of Torrefranca and Otadoy (2022) presents a morphometric analysis on the Philippine Bohol Island. In their study, watershed delineation and extraction of the drainage network was performed by applying the qswat plugin of QGIS on a DEM of 5 m × 5 m cell size. A total of 27 morphometric parameters were derived directly from the geometries using GIS software or calculated with spreadsheets. The parameters were compared with other values from the relevant literature in order to determine the run-off peaks and susceptibility to erosion. Diakakis (2010) used a set of GIS tools from the proprietary ArcHydro toolbox for flood hazard mapping in Greece. Their approach was based on an analysis of flow direction, flow accumulation and subcatchment delineation with a DEM with a spatial resolution of 3 m. Comparable open source tools are available, e.g. in QGIS the by integrating the GRASS (Neteler et al., 2012) processing provider or the SAGA toolbox (Conrad et al., 2015). Using Manning roughness coefficient values estimated by means of open land use data from CORINE land cover (CLMS, 2021a), Diakakis (2010) created a flow velocity grid which was used to derive hydrographs and peak discharges of the delineated subcatchments in the subsequent steps of the method. In the final step, the catchment areas were assigned to five hazard classes based on the peak discharges.

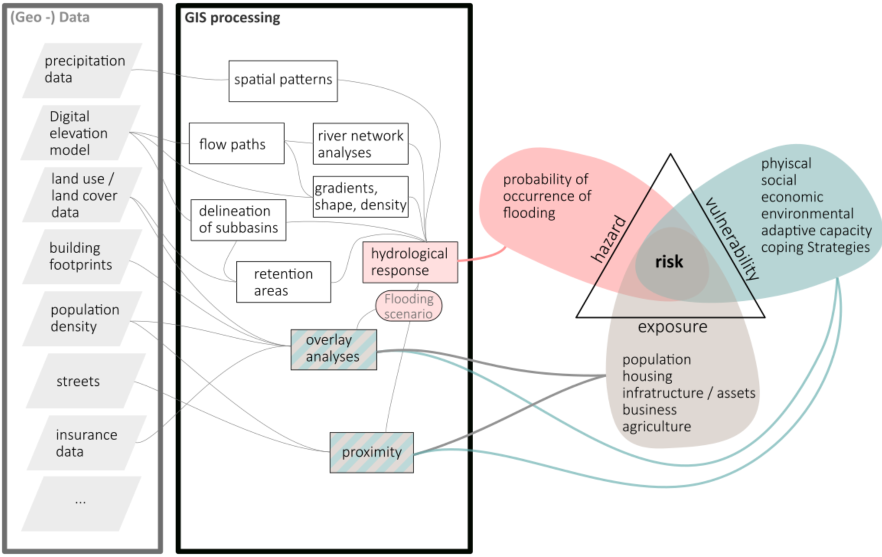


Figure 3.3.: Exemplary GIS processing sequence for flood risk assessment as performed in a workshop of the OSWeGe project (section 5.1). A selection of possible input data is presented on the left side of the illustration. A flooding scenario is developed on the basis of spatial analyses of precipitation, flow paths and catchment parameters. Overlay (intersection) or proximity analyses with land use and population data enable an assessment of exposure and vulnerability. The illustration of risk triangle (cf. section 3.2.3) was adapted from de Brito et al. (2017)

GIS can also be used to measure aspects of vulnerability, such as spatially referenced information on financial resources, public and individual protection facilities, age structure and risk awareness (Fernandez et al., 2015). For example, O'Neill et al. (2016) used questionnaires and so-called "cognitive maps" to investigate how residents of the town of Bray on the River Dargle in Ireland perceived their own vulnerability. Their study used a distance analysis to identify proximity to the watercourse and proximity to areas previously affected by flooding as the decisive factors for flooding awareness. A common approach to estimating exposure using GIS is to perform an overlay analysis, as flooding is a spatially clearly delimited event (Arvidsson et al., 2022). Evaluated metrics include the number of buildings, population density or number, location of major transportation routes or infrastructure, and percentage of affected land use classes within an affected area (Ziegelaar & Kuleshov, 2022). The required data on infrstructure can be retrieved from the OpenStreetMap project worldwide (Geofabrik GmbH, n.d.-a). Arvidsson et al. (2022) propose spatial analysis and network analysis in GIS to provide information on cascading effects. In particular, critical infrastructures such as power grids, drinking water networks or sewerage systems are spatially assessed in their method, as they often extend over large supply areas, so that a failure at one point has consequences for other areas far beyond those directly affected by the flooding.

Fernandez et al. (2015) developed a GIS-based model for flood risk management, in which different scenario-based designs of development options can be evaluated using spatial factors and constraints. The multicriteria analyses of the method represent a an "integrated" approach as mentioned in section 3.3. Interfaces to hydraulic and hydrological modeling software can integrate temporal assessments of flooding (Schilling & Tränckner, 2022). The visualization of analysis and model results in different spatial resolutions using GIS also allows cascading effects to be included in planning (Arvidsson et al., 2022; Guse et al., 2015).

Combining GIS and machine learning techniques can enhance spatial analyses of large datasets and patterns for flood risk assessment (Tran et al., 2024). The study of Agarwal et al. (2023) investigated extreme annual rainfall patterns across six north-eastern Indian states with spatial interpolation (Kriging) and methods such as multiple linear regression, generalized additive models, and random forest. In general, the application of machine learning techniques to remote sensing data (see below) in flood risk assessment is a rapidly developing field of research. However, because they require advanced computing skills and high-quality large datasets (Abraham et al., 2023), these techniques have yet to become established among river management practitioners.

Monitoring with mobile GIS and remote sensing data

The keyword "monitoring" generally refers to measures and techniques that record and, if necessary, evaluate temporal and / or spatial changes to (sub)systems. Monitoring is applied, e.g. for land use changes, deforestation, erosion and morphology, or the general condition of aquatic and terrestrial ecosystems using indicators (Chatrabhuj et al., 2024). Another important field of application is monitoring the distribution and abundance of aquatic and semi-aquatic species. GIS-based mapping can be used to track migration movements, changes in species diversity, as well as changes in their habitat conditions. Nguyen et al. (2023) evaluated the effect of salinity intrusion patterns on a river ecosystem in Vietnam, using the distribution of meiofauna as the main indicator. Monitoring can also be part of a planning process for conservation measures or be used to assess the failure or success of a measure after it has been implemented.
Increasingly, traditional monitoring through field measurements and mapping is being supplemented or replaced by combined digital methods that integrate mobile GIS applications and remote sensing data into the monitoring process (Chatrabhuj et al., 2024). Mobile GIS applications which can be installed on smartphones or tablets, are applied to record geometries (points, lines, polygons) and associated attributes in the field. As an alternative to proprietary applications (e.g. ArcGIS Field Maps) open mobile GIS such as QField (OpenGis.ch, n.d.) or Mergin Maps (Mergin Maps, n.d.) are popular because they can easily combined with QGIS. Either the device's internal GPS or an external GPS receiver can be used to get the current position of the mapper.

In most cases, cloud-based services provide data transfer to desktop or web GIS software (Nowak et al., 2020). Mobile GIS is used, for example, for mapping endangered or invasive species (Nowak et al., 2020), or to involve citizens in the mapping of water-related objects and floods (Canevari-Luzardo et al., 2015; Fazeli et al., 2015).
Remote sensing methods are used to monitor river morphology in order to identify processes such as erosion and sedimentation in river systems (Colby, 2019; Nones, 2020). This information is crucial for the long-term management of watercourses, as it provides information on how the structure of the watercourse is changing due to natural and anthropogenic influences and where renaturation measures may be necessary. The evaluation of satellite images during flood events in GIS enables precise monitoring of the extent of flooding, sometimes in real time. The data effectively supports emergency services and decision-makers in assessing potential risks, developing emergency response plans and taking appropriate precautionary measures (Chatrabhuj et al., 2024; Rahman & Di, 2017).
Monitoring land use and land cover (LULC) changes within catchment areas (e.g. in Guse et al., 2015) requires the availability of appropriate geodata covering different time periods. These are often derived from remote sensing data. For Europe, for example, geodata on land use is available from the CORINE project (Coordination of Information on the Environment) of the EU Commission's Copernicus Land Monitoring Service (CLMS). As part of the program, national land cover maps were combined into a harmonized data set with 44 land use classes under the name "CORINE Land Cover". The dataset has so far been published for the six reference years 1990, 2000, 2006, 2012 and 2018. The next update for the reference year 2024 is planned for 2026 (CLMS, 2021a). It is an open data set as defined by the Commission Delegated Regulation 1159/2013/EU, which means open access to the data or service (Art. 1), free of charge (Art. 4), with the right to redistribute and modify (Art. 7)., and the obligation quote the source of the data (Art. 8). Comparable geodata is available for the USA under the name "National Land Cover" with a CC0 license (Homer et al., 2020; U.S. Geological Survey, n.d.). Worldwide coverage is provided by the CLMS

dataset “Global Dynamic Land Cover” (Buchhorn et al., 2021).

GIS as a communication tool

Analogue and digital maps contain a high density of information. Factual information is visualized via points, lines and areas in which quantitative or qualitative properties are communicated via the choice and intensity of colors, line thickness, hatching and shape. In addition, maps always provide contextual information. They show where something is located, which objects are nearby, and which flow paths or water bodies serve as a connection between areas and objects. This combination makes maps the ideal medium for presenting complex issues in river management in a clear and compact way, e.g. as:

- **maps in third party communication / order management**. They inform the companies carrying out the field work, for example by highlighting sections of the river or infrastructures to be maintained. At the same time, such maps contain the necessary information on possible obstacles and access routes. This application example was described by participants of the OSWeGe workshops (section 5).
- **flood hazard maps and flood risk maps**. They are an essential element of flood risk management. For example, the European Flood Risk Management Directive (2007/60/EC) requires hazard maps for flood hazards and risks at three probability levels (Arvidsson et al., 2022). They indicate the flow paths of flooding, the expected maximum flood extent and flood height. By making them available, stakeholders such as local authorities, associations, fire departments, organizations and residents with their resources (personnel, tools, knowledge) can be better integrated into the risk management process (Jalink & Dieperink, 2024).
- **maps in participation processes**. In the simplest case, they provide information about construction projects / measures and increase their acceptance among those affected by presenting the reasons for consideration in an understandable visual language. Using interactive web GIS or corresponding mobile applications,

citizens can independently record information, e.g. water levels, or point out (spatially located) grievances (Canevari-Luzardo et al., 2015; Chatrabhuj et al., 2024). With such tools stakeholders can actively contribute in decision making processes, which is, for example, described as "inclusiveness" in integrated management designs by Jalink and Dieperink (2024).

The provision of geodata allows the target group to carry out their own data analyses, filter and query data and select visualization options. In the simplest case, the information is provided as a map view that can be printed or displayed in a web browser, depending on the specific purpose. The provision via browser-based GIS applications enables the interactive query and data input of geodata. An overview of open source web GIS software for water resources data was published by Swain et al. (2015). The open source JavaScript library "OpenLayers", for example, has been applied by Zander and Kralisch (2016) to set up an information system for river data. "Leaflet" is a comparable JavaScript tool for the integration of interactive maps in websites (Löwe et al., 2022). Web maps with both OpenLayers and Leaflet can directly be built via plugins in QGIS (Graser et al., 2025).
A more interoperable use of geodata or maps in GIS is possible via geoservices, for which corresponding standard protocols have been developed by the Open Geospatial Consortium (OGC). The web map service (WMS) protocol, for example, defines the provision of maps as georeferenced images. In its enhanced version, the Web Map Tile Service (WMTS) efficiently delivers map images as tiles. Web Feature Services (WFS) provide objects with vector geometry that can be processed by the user in locally installed GIS or Web GIS. The standard protocol Web Processing Service (WPS) defines operations and requests to a server which enables the user to perform spatial analyses of geodata as a web service. Moreover, such data services can be integrate in other websites or mobile apps. For example, the data provided by data servies of PEGELONLINE (WSV, n.d.) is part of more than 30 external applications, e.g. in logistics (BMI, 2021). Geoportals are special data platforms that combine many of these functionalities (OGC, 2024). Depending on the implementation, they are used for the

exchange of geodata between different stakeholders, provide the associated metadata, contain map and query interfaces, and can be provided with access rights or restrictions for individual user groups (Hübner et al., 2017). Geodata infrastructures such as GDI-DE are used to link the geodata tagged with metadata from various portals (Weke et al., 2024b). Further examples for open geodata platforms can be found in table 3.4.

3.4.2. Modeling in water management

"Modeling" in water management refers to tools and concepts that provide a simplified representation of various components of water infrastructure and their associated processes. These components may include for example sewer networks, water bodies, and catchment areas, along with their water-related processes such as flow, evaporation, substance transport, and chemical reactions. Modeling tools are used both to enhance understanding of past events and to predict scenarios as a basis for planning. Various types of models can be distinguished based on characteristics such as complexity, functionality, and scope.
Hydrological models are employed to depict processes within the catchment area, in order to calculate runoff formation and runoff concentration. They can be used for example to evaluate the effect land use and land cover changes on evaporation, infiltration and runoff (Salvadore et al., 2015). Hydraulic models are mathematical representations of water flow along specific flow paths, utilizing energy equations to describe the movement of water. With regard to water flow and sediment transport, different hydraulic modeling dimensions are considered depending on the specific issue. In one-dimensional models, water levels (and thus energy levels or pressures), flow velocities, and flow rates are usually calculated in node-edge models using energy equations in the main flow direction. Two-dimensional models are used to map the water flow across a specific area (cf. Guse et al., 2015). They are used, for example, in flood risk management (e.g. Buttinger-Kreuzhuber et al., 2022; Cimpianu & Mihu-Pintilie, 2019; Sañudo et al., 2020). Due to the high computing capacity required, three-dimensional models are gener-

ally used for small-scale problems, for example to map flows around building components such as bridge piers and fish ladders, or to calculate vortex formation at outlet. Additionally, a distinction is made between stochastic and deterministic simulation models. Within deterministic models, the state of a system at a given moment is determined by the input parameters. Stochastic models use random variables and probability functions to describe unpredictable systems and processes (cf. Beven, 2019; Beven, 2024) With regard to the time interval, models for individual scenarios as well as long-term models are common in water management (e.g. Kachholz & Tränckner, 2020). Whereas simulation models used to be developed for specific issues, many applications available today cover various areas of application as so-called coupled models (Buttinger-Kreuzhuber et al., 2022).

All of the model types mentioned here have in common that they require input spatial data on modeled infrastructures. After the model has been built, several calibration steps are typically performed before the model can be validated with another reference data set. The calibration of models can be described as a discipline in its own right. Detailed discussions on this topic can be found, for example in Beven (2024). Instead, the focus here will be on the question of data origin and preparation. With the availability of information on catchment areas, precipitation data, and soil parameters, the types of models and modeling philosophies have also changed (Todini, 2007). In the early days of modeling, parameters had in parts often to be estimated. With the availability of measuring instruments, digital processing software for spatial data (GIS), and statistical software, more and more complex preprocessing steps and more extensive calibration steps are in use (Beven, 2024).

Where available, open official geodata is the preferred option for model setup and boundary conditions. Environmental relevant geodata such as river geometries can be retrieved from the regional environmental data portals (cf. table 3.4). For example in M-V, geodata is provided with a CC-BY-SA license (LUNG, n.d.-a). Further basic geodata can be downloaded from the open geodata website of M-V. For the calibration and validation of hydraulic models flow and water level data are crucial. In the past, these were collected as part of complex measurement campaigns. Today, automatic gauges have been installed at many locations, at least on larger water bodies (Crochemore et al., 2019). For smaller tributaries, geostatistical methods have been developed to regionalize and transfer parameters, e.g. as part of SAGA GIS (Conrad et al., 2015) or the corresponding SAGA toolbox in QGIS.

This is where open geodata shows its great potential. The availability of digital climate-related data such as rainfall and temperature, provided openly by official meteorological institutions is a key driver for model setup. In the past, the lack of rainfall data in suitable temporal and spatial resolutions was considered a "weak point" in hydrological modeling (Fletcher et al., 2013). In Germany, today rainfall data can be retrieved from the German meteorological service/*Deutscher Wetterdienst* (DWD) open data website with a Creative Commons license (DWD, n.d.-b). Besides rainfall time series from meteorological stations all over Germany, there are rainfall radar data from the RADOLAN routine available. These data are employed in numerous (hydrological) models (e.g. by Bormann et al., 2024; Hovenbitzer, 2023; Kachholz & Tränckner, 2020). Data from official gauges (flow rates, water levels, location of the gauges, etc.), which are needed for calibration, is published in Germany with the *Datenlizenz Deutschland – Zero – Version 2.0* on the information system "PEGELONLINE" (WSV, n.d.). In addition to downloading the data, the data of this provider can be accessed by various data services (WMS, web feature service (WFS), REST-API). Other countries provide comparable data sets, as shown by the review on openly accessible river flow data worldwide by Crochemore et al. (2019).

Because modeling is closely linked to spatial data, GIS techniques, water management, and modeling software have in many respects evolved in parallel (Colby, 2019). Accordingly, the distinction between the two software groups is often blurred. Conceptual models, in particular, are increasingly being implemented directly in GIS environments (e.g. Rossetto et al., 2018). Modeling software components can be added as plugins or linked via programming interfaces (Cimpianu & Mihu-Pintilie, 2019; Guse et al., 2015; Park et al., 2019; Schilling & Tränckner, 2022).

Conversely, modeling software often incorporates a GIS or CAD component. Commercial/proprietary modeling software in particular offers users convenient user interfaces with corresponding import tools for spatial data (cf. Swain et al., 2015). Nevertheless, open source components also fulfill an important function in the field of modeling. The above-mentioned model types rely on numerical solvers to approximate solutions to the governing equations. Here, many open source software solutions can be found (even for proprietary models), or those that have been derived from open source software.
A prominent example is the Stormwater Management Model. The first version of the model was published in 1971 as public domain software. Since then the model has continuously upgraded with new functions by the US EPA. Since 2016 there is also a community-based version of the software. As the source code has always been freely available, there are numerous further developments of SWMM. Moreover, other modelling software packages –open-source as well as proprietary – use the SWMM engine. A (non-exhaustive) list of the various applications is shown in Table A.1 in annex A. For example, because SWMM itself was a pure command line tool in the beginning, the first graphical user interfaces (GUIs) such as PCSWMM, XPSWMM, SWMENU, SWMM-DUET and WSWMM were developed in the 1980ies and early 1990ies (Shamsi, 1997). Starting in the late 1990ies, SWMM was integrated into other graphical GIS, e.g. as part of commercial software products such as SWMMTools (Heineman, 2001), InfoSWMM (Boulos et al., 2006). Later, interfaces to programming languages such as Python (Banik et al., 2014; Pathirana, 2024), Matlab (Riaño-Briceño et al., 2016) or R (Leutnant et al., 2019) were implemented, from which SWMM can be controlled.
Likewise, packages were released that perform specific processing steps in the entire process, from model construction to evaluation and visualization of the model results, e.g swmmout (Townshend, 2012), swmmtoolbox (Cera, 2025) or hymo (Nguyen, 2018). Because they are published with open source licenses, other packages such as PySWMM (McDonnell et al., 2020) or swmm_api (Pichler, 2022) incorporate parts of these to provide the user with a all-in one solution. Addi-

tional functionality has been integrated into SWMM itself by extensions such as SWMM-UrbanEVA which added advanced evapotranspiration modelling options (Hörnschemeyer et al., 2021; Kachholz & Tränckner, 2020). The latest developments include coupled models, in which, for example, SWMM performs the hydraulic calculations within a river, while the processes of runoff generation or surface runoff take place in a 2D model (Buttinger-Kreuzhuber et al., 2022; Leandro & Martins, 2016; Sañudo et al., 2025; Sañudo et al., 2020). The numerous applications derived from the original open source source software clearly proof the innovation argument by Paderta (2012). The available source code was not only reused in the projects that followed. Many of the developed SWMM-based applications are in turn open source projects.

4. Exemplary applications of open data and open source software

This chapter highlights the advantages of open data and open source software mentioned in Chapter 2 using two application examples that have already been published as peer-reviewed articles.

4.1. Estimation of Wastewater Discharges by Means of OpenStreetMap Data

4.1.1. Introduction

Sewage networks for the transport of wastewater from industrial, commercial, and residential areas to sewage treatment plants are essential elements of the water infrastructure. As the construction and maintenance of wastewater networks are cost-intensive, a large number of research projects are dedicated to the optimization of such infrastructures (Navin & Mathur, 2016).

In recent years, the focus has been on the development of optimization algorithms for layout and component size of sewer networks (Duque et al., 2016; Navin & Mathur, 2016; Steele et al., 2016; Zhao et al., 2016). Wastewater discharges as a main boundary condition for optimization are often regarded as "given" (Duque et al., 2016; Navin & Mathur, 2016) without going into details in terms of data sources. In other works, the amount of wastewater is merely estimated, e.g., based on the drinking-water consumption of larger supply areas and provided with a peak factor (Zhao et al., 2016). Here, wrong assumptions about the amount of wastewater may lead to an oversized or undersized system (Campos & von Sperling, 1996).

In the work of Willuweit and O'Sullivan (2013) a combination of models is used to simulate water demand, water supply, wastewater, and runoff in urban areas, under changing land-use and climate scenarios. In the water balance approach, it is assumed that the amount of wastewater produced corresponds to the domestic water consumption. To estimate the water demand, flows monitored in district metered areas are evenly distributed to cells of 4 ha size, using GIS software.

To determine the amount of wastewater inflow into existing drainage systems, the worksheet 118 (DWA, 2020c) of the German association for water management, wastewater and waste / *Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall* (DWA) recommends measurements of dry weather runoff with long measurement periods, if possible, in different seasons, as well as additional measurements in commercial, industrial, or tourist areas. However, the collection of data with a temporally and spatially high-resolution involves a great deal of effort. In addition, data protection and company secrecy restrict the availability of such datasets. Hence, procedures are needed to determine the volume of wastewater with high spatial resolution, based on freely accessible data.

A common approach to determine the domestic water use is by population figures. For instance, Schiller and Bräuer (2013) present a method using population figures from official statistics, disaggregated by building footprints from ATKIS (official German topographic–cartographic dataset). The main part of their method is the classification of three settlement/municipality types and ten building types based on topographic geodata and building footprints from the ATKIS basic digital elevation model (DEM) with GIS tools. Building footprints and information about the use of buildings can also be derived from OpenStreetMap (OSM) datasets. Bakillah et al. (2014) use points of interest (POI) from OSM as indicators for high or low population densities, to disaggregate population figures of the city of Hamburg into a grid (500 m^2 per grid cell). They then distribute the population of each grid cell proportionally to the OSM building footprint size within it. Kunze (2013) uses building attributes stored in OSM data to describe the share of non-residential use in existing buildings. Fan et al. (2014a)

derive different building types from semantic information and the shape of the building floor area in OSM.
OSM geodata are maintained and continuously expanded by the OSM community. This way of generating and collecting data is called VGI (Goodchild, 2007). Since the data are collected by nonprofessionals, the preparation and quality assurance of VGI data, in general, and of OSM data, in particular, are much more demanding than of data collected specifically for a particular research question. A large number of articles is devoted to quality assessment and assurance at VGI in general (Bégin et al., 2013; Dorn et al., 2015; Haklay, 2010; Koukoletsos et al., 2012; Leibovici et al., 2017; Meek et al., 2014; Senaratne et al., 2016). Particularly for OSM building datasets, the data quality is the subject of various studies regarding completeness (Hecht et al., 2013; Törnros et al., 2015), building density (Zhou, 2018), and accuracy of geometries (Fan et al., 2014b). Heterogeneity and incompleteness of the data is a common challenge. A higher data density and accuracy of OSM buildings in cities compared to rural regions can be explained by the number of local participants in the OSM project, which is generally larger in cities (Bégin et al., 2013; Dorn et al., 2015; Werder et al., 2010). The same findings are noted for land-use data (Dorn et al., 2015). In addition, incorrect data collection by nonprofessionals is a common difficulty, as is the lack of metadata or the ability to verify data (Meek et al., 2014).
Nevertheless, VGI has proved to be a useful data source in many fields of application and scientific questions, since — as the word “volunteered” suggests — they are voluntarily made available to the public and, thus, the user does not have to spend any time on data collection. OSM data are freely available and may be used under the Open Database License (Alhamwi et al., 2017). Application examples for VGI are the mapping of flood hazards (Fazeli et al., 2015), disaster management (Horita et al., 2013), modeling of energy infrastructure (Fazeli et al., 2015; Medjroubi et al., 2017), validation of land-use maps (Fonte et al., 2015), or ecological monitoring (Connors et al., 2012). The application of OSM data in urban-planning contexts has so far been investigated primarily in the field of transport infrastructure planning (Baloian et al., 2015; Dimond

et al., 2017) band the analysis of settlement structures (Kunze & Hecht, 2015; Schiller & Bräuer, 2013). In the field of urban water management, the OSM road network was used to generate virtual wastewater networks (Blumensaat et al., 2012; Mair et al., 2017). The connecting element between settlement structure and sewage network was not considered in the mentioned work: wastewater from residential buildings, industry and commerce, or other uses that is transported to a treatment plant along the sewage network. In this article, a method for the estimation of the wastewater volumes based on OSM data is presented. The parameters used for the calculations are optimized by comparing the estimated wastewater volumes in the catchment area of WWTPs and sewage pumping stations (SPSs) with measured dry weather inflows. As a sample application, estimated wastewater discharges are spatially intersected with land-use plans, to develop a scenario-capable tool for the integral planning of settlement structural measures.

4.1.2. Materials and methods

Study area

The "Regiopolregion Rostock" is located in the northeast of Germany (see Figure 4.1, left). A regiopol region consists of a smaller large city with the surrounding rural region. Urban and rural areas differ in building types, infrastructure, land use, and population density (Küpper, 2016), leading to a large heterogeneity concerning amount and variability of mass flows, such as wastewater (ATV, 1997). The socioeconomic center of the area is the city of Rostock, with approximately 200000 inhabitants. The communities in the surrounding area, by contrast, have a more village-like or small-town character. The area of responsibility of the WWAV, purple boundary line in figure 4.1 covers the entire urban area of Rostock with a sewer connection rate of 99.7 %, as well as 29 municipalities in the south and east of the city. Wastewater treatment is mainly performed at the central wastewater treatment plant in Rostock (point 1 in Figure 4.1), with a capacity of 400000 population equivalents (PE). Because of small slopes in the coastal region, wastewater is transferred to the central WWTP via 310 SPSs. With 14 further

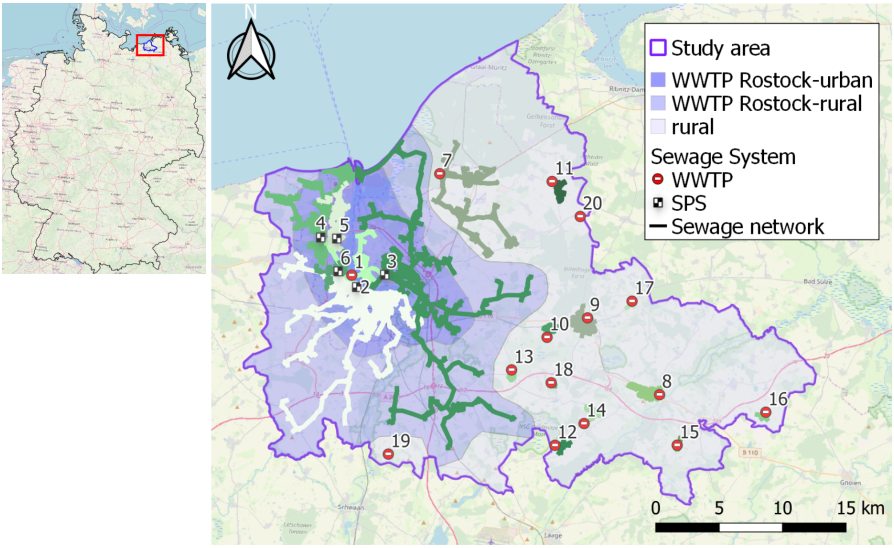


Figure 4.1.: Location and extent of the study area: The sewage network colors indicate different catchments; from the catchments of the five largest sewage pumping stations (SPSs) (Points 2 to 6), which cover rather rural areas (light purple), as well as rather urban areas (dark purple), wastewater is transferred to the central wastewater treatment plant (WWTP) of Rostock (Point 1); background map: OSM ©OSM contributors.

central sewage treatment plants in the association area, with capacities between 49 and 4999 PE, a fairly high connection rate of 87.6 % is also achieved in rural areas. In addition, there are 1989 decentralized small sewage treatment plants (up to 49 PE) (WWAV, 2019). For the method presented here, building polygons and land-use polygons are obtained from the OSM provider Geofabrik (for Mecklenburg-Western Pomerania: Geofabrik GmbH (n.d.-b)). The dataset clipped to the study area contains 79053 building polygons. Basic elements in OSM are points/“nodes” (points of interest or centroids of surfaces), open or closed lines/“ways”, and “relations” (relationships between objects, such as groups of objects). All OSM elements get their properties from attributes/“tags”, each consisting of a key and a value (Ballatore et al., 2012). Polygons are constructed by closed lines with the attribute “area=yes” and with certain tags like “building=*” or “landuse=*” (“*” being a particular attribute), which are assigned exclusively to areal elements. In OSM, buildings, in particular, are assigned by the tag “building=*”. For example, a building is already clearly identified by “building=yes”, but it can also be more precisely labeled by other values (e.g., “building=hotel”). However, an element declared as a building could also get the property “hotel” by “tourism=hotel”. For the assignment of OSM tags, the OSM Wiki website provides a multitude of hints and examples. These can be regarded as a guideline more than a fixed set of rules. New tags can be proposed, changed, and discarded by the OSM community (Ballatore et al., 2012). Additional information on land use, as well as population figures of municipalities and municipal boundaries, is taken from official data (e.g., ALKIS, provided by regional administrations (LAiV, n.d.-a)). A digital map (shapefile) of the sewage network and measured values of the daily inflow to WWTPs and SPSs from the regional wastewater association WWAV are used for the optimization process.

Generation of wastewater volume per building

GIS software is used to link OSM building polygons with information on land use (OSM: land use, ALKIS) and location (municipality, WWTP catchment area) by spatial intersection. The further calculation of the wastewater volume is performed in four steps using R scripts (R Developement Core Team, 2011). An overview about the method is illustrated in figure 4.2. According to the wastewater discharge components described by the German DWA worksheet 118 (DWA, 2020c), buildings are classified into “residential buildings”, “industrial buildings”, and “commercial buildings” in step 1. Buildings that combine different uses (e.g., retail trade with living space on the floors above), are assigned to the type “mixed-use buildings”. Buildings that (presum-

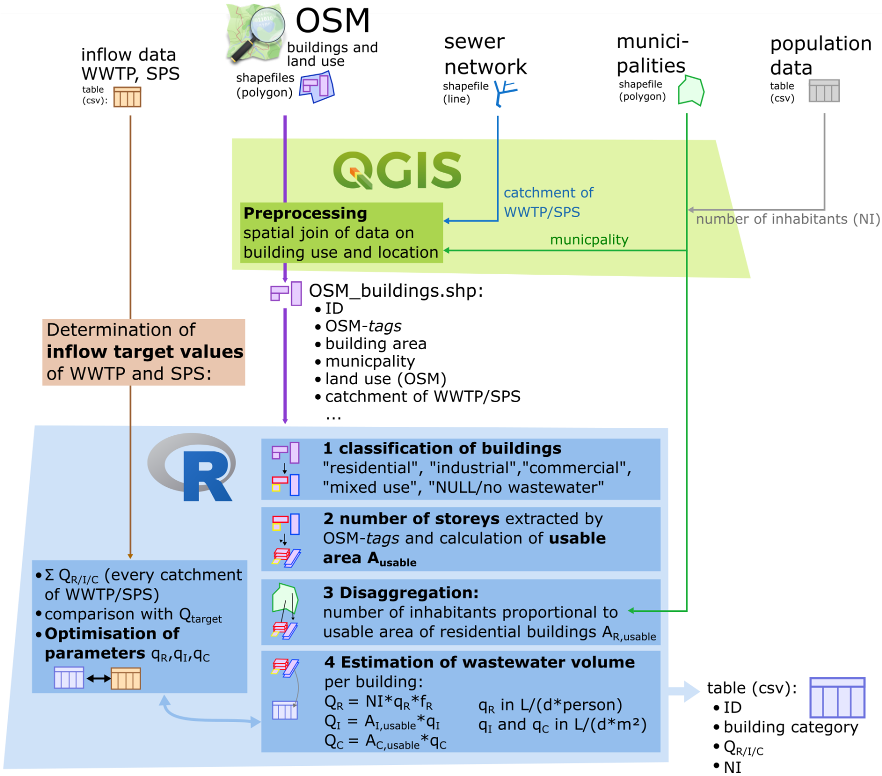


Figure 4.2.: Flowchart of the method for estimating wastewater volumes on a building level.

Table 4.1.: Used OSM-tags (abstract) for the classification of buildings

Residential	**Commercial**	**Industrial**	**NULL**
apartments	airport_terminal	cowshed	abandoned
detached	commercial	dock	allotments
dormitory	doctor	farm	cabin
house	hall	greenhouse	carport
private	hospital	industrial	collapsed
residential	hotel	manufacture	container
semi	kiosk	mill	construction
semidetached_house	museum	stable	garages
terrace	office	storage	gasometer
yes	public	sty	ruins
...	...	...	...

ably) do not discharge wastewater into the network, are assigned to the “NULL” category. The classification process is carried out by various attributes:

1. OSM tags of the buildings, e.g., “building”, “leisure”, and “amenity” (see Fan et al., 2014a). Some examples are shown in table 4.1.
2. OSM tags of land-use polygons on which a building is located.
3. If none of the former is stated: land-use information derived from ALKIS.

In step 2, the number of floors is – if available – directly extracted from OSM tags (“levels”), derived from the building height (“building:height”) or estimated on the basis of the usage class of the building. The usable area of a building is calculated by multiplying the floor area with the number of floors, less 5 % as unusable area. The number of inhabitants (NI) of every municipality is then disaggregated proportionally to the usable area of each of its residential or mixed-use buildings (step 3).
Step 4 of the algorithm is the calculation of wastewater discharges per building by equations 4.1 (residential buildings), 4.2 (industrial buildings) and 4.3 (commercial buildings). For mixed-use buildings, the

equations 4.1 to 4.3 are employed proportionately.

$$Q_R = NI \times q_{\mathrm{R}} \times f_{\mathrm{R}} \tag{4.1}$$

$$Q_I = A_{\mathrm{I,usable}} \times q_{\mathrm{I}} \tag{4.2}$$

$$Q_I = A_{\mathrm{C,usable}} \times q_{\mathrm{C}} \tag{4.3}$$

Discharge rates for residential (q_{R}) (in $\mathrm{L\,person^{-1} d^{-1}}$), commercial ($q_{\mathrm{C}}$), and industrial buildings (q_{I}) (each in $\mathrm{L\,m^{-2}\,d^{-1}}$, related to the building footprint area) are determined by the optimization algorithm described in the following section. It is assumed that a large proportion of the inhabitants of the surrounding municipalities does not work at their place of residence. As a result, a part of the domestic wastewater is not produced in these municipalities, but is already contained in the wastewater from commercial buildings. This fact is taken into account in the calculation by a "rural factor", f_{R} (a fixed value for every municipality; between 0.6 and 1), depending on the population density of the municipality.

Optimization of parameters

The wastewater volume, $Q_{\mathrm{catchm},n}$ which is generated in the catchment area, A_n, of a sewage treatment plant or a pumping station with the number n, consists of domestic, industrial, and commercial wastewater:

$$Q_{\mathrm{catchm},n} = \sum Q_{\mathrm{R},n} + \sum Q_{\mathrm{I},n} + \sum Q_{\mathrm{C},n} \tag{4.4}$$

Catchment areas of pumping stations and sewage treatment plants are defined along the sewage network in the area of responsibility of the WWAV (see Figure 4.1). For this purpose, buildings are inked to the nearest sewer by GIS queries. Flow paths are determined by using routing scripts from the QGIS plugin "WaterNetAnalyzer", which was developed by the authors within this study (QGIS Project, n.d.-b). The amount of wastewater, Qcatchm, generated in the catchment area of 15 WWTPs (Points 1 and 7–20 in Figure 4.1) and 5 main SPSs (Points 2–6 in Figure 4.1) are compared with corresponding measured values of the daily inflow. The first quartile of dry weather inflows (1 January 2017 to 31 December 2018) is selected as the target value for each of the five main pumping stations and the WWTPs in the study area. Dry weather inflow is assumed, if the total precipitation measured on the day itself and on the previous day is below $0.1\,\mathrm{mm\,d^{-1}}$. Where daily values of the inflow are not available, the average annual inflow of wastewater (2013–2017) to small WWTPs converted to a daily value is used as a target. The parameters q_{R}, q_{I}, and q_{C} are optimized by minimizing the deviation of the generated wastewater quantities from the target value (equations 4.5 and 4.6)

$$min \sum (Q_{\mathrm{target},n} - Q_{\mathrm{catchm},n})^2 \tag{4.5}$$

Replacing $Q_{\mathrm{catchm},n}$ in equation 4.5 with equations 4.1 to 4.4 equals the following:

$$\begin{aligned} min \sum (Q_{\mathrm{target},n} - (\sum NI_{\mathrm{catchm},n} \times q_{\mathrm{R}} \times f_{\mathrm{R}} \\ + \sum A_{\mathrm{I,usable,catchm},n} \times q_{\mathrm{I}} + \sum A_{\mathrm{C,usable,catchm},n} \times q_{\mathrm{C}}))^2 \end{aligned} \tag{4.6}$$

Optimum parameter combinations are determined using the R function “optim()” with the Nelder-Mead method (Nelder & Mead, 1965), and the R function “lm()” for linear regression. The values used for optimization are presented in detail in Table A.2

Application example: aggregation at LUP level

Land-use plans (LUPs) represent the intended urban development of a municipality. They are an essential tool for the integral planning of structural settlement measures in regiopol regions. A catchment yield factor, $q_{\mathrm{LUP},i}$ (in L/(s ha)), is derived for each subarea, i, of the LUP by spatially joining the estimated wastewater volume in GIS with the LUP of the City of Rostock (see Figure 4.3). For this purpose, wastewater discharges are aggregated in every LUP subarea and divided by its area A_{LUP} (equation 4.7).

$$q_{\mathrm{LUP},i} = \frac{\sum Q_{\mathrm{LUP},i}}{A_{\mathrm{LUP},i}} \tag{4.7}$$

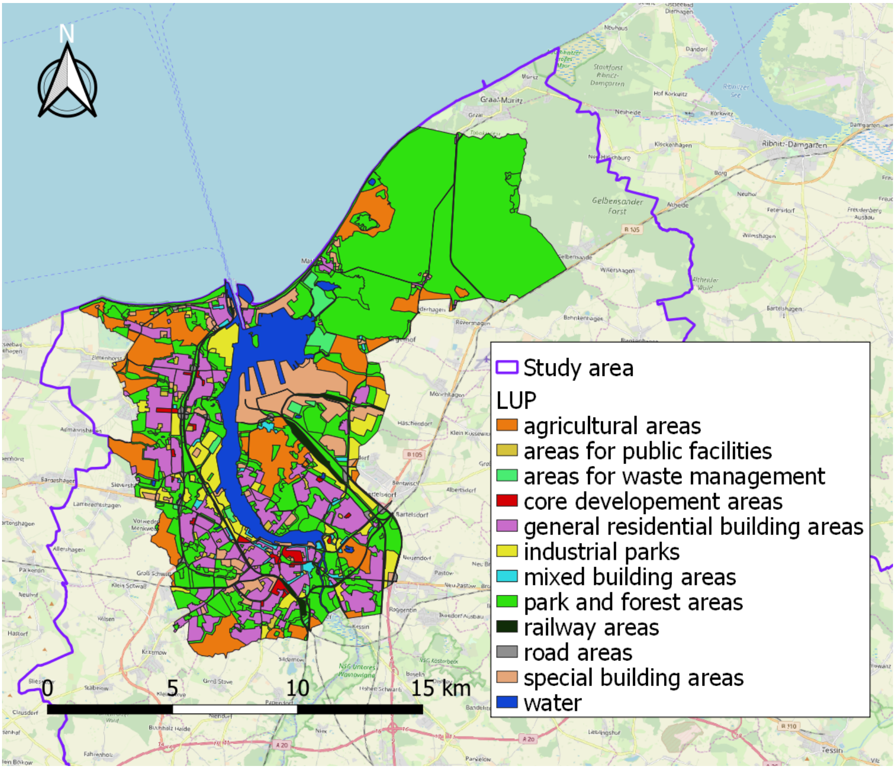
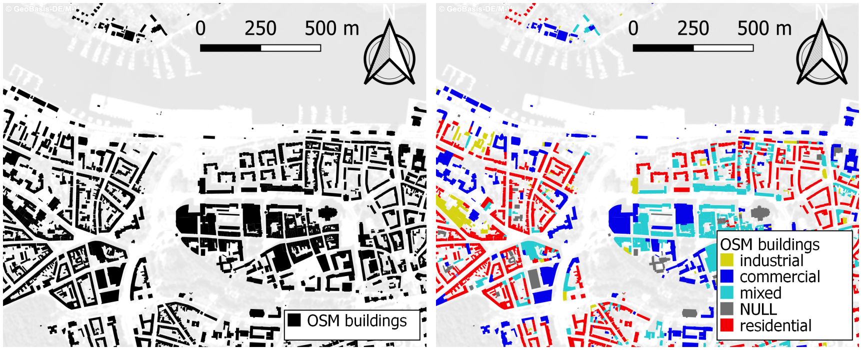


Figure 4.3.: Land-use plan of the city of Rostock; background map: OSM ©OSM contributors.

The range of the catchment yield factors sorted by types of land use (e.g., residential area, mixed-use area, etc.) can be used in planning scenarios. For example, the effect of a planned industrial park on a sewage network can be investigated in models by multiplying its intended area with the median catchment yield factor of industrial areas.



(a) (b)

Figure 4.4.: OSM buildings of the Rostock city center: (a) before classification and (b) after the classification process.

4.1.3. Results and discussion

Classification of buildings

The classification of the buildings into the mentioned categories is based on OSM tags and information on real land use from ALKIS data. Figure 4.4 shows the result of the classification in the inner-city area of the city of Rostock.

In the catchment of WWTP Rostock, the share of residential space is 67 %. Moreover, 25 % of the building areas are identified as commercial, and 8 % are industrial areas. However, the distribution of the area categories also varies within the urban area (cf. Figure 4.5). In the catchment area of the SPS at point 6, the share of residential areas is only 35 % . In contrast, 75 % of the building areas are categorized as residential in the catchment of the SPS at point 4, where larger multistory blocks of flats are located. In the rather rural part of the study area, "residential" accounts for an average of 82 % of the building areas, 11 % are commercial and 7 % are industrial building areas. Absolute values for each area type are provided in Table A.2. An essential element of uncertainty is the unknown completeness and correctness of the OSM

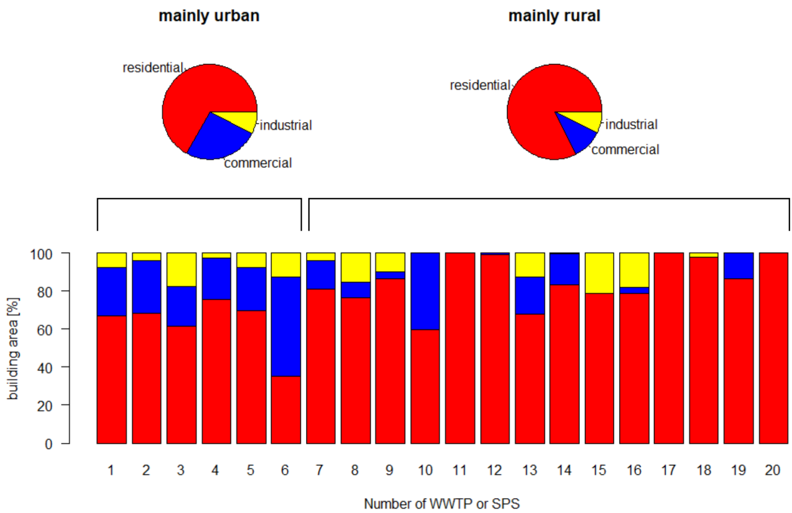


Figure 4.5.: Classification of buildings´ areas in the study area by building type.

building polygons. Goetz and Zipf (2012) estimated that, at the time of their investigation only approximately 30 % of all building geometries in Germany are recorded in OSM. They expected that continuous contributions of the OSM community would lead to an increasing percentage here, up to 90 % within a few years. Even without a more precise evaluation, it is assumed that this figure will not yet be reached in the study area, as in certain villages, hardly any buildings have yet been marked (cf. Figure 4.6). A large number of missing building geometries can be expected in the rural municipalities (Hecht et al., 2013). A comparison of OSM buildings with official cadastral data can help to identify missing geometries here (Törnros et al., 2015). Irrespective of this, the OSM dataset for the city of Rostock is very extensive, as the Cadastral Office of Rostock donated a building dataset to the OSM project in 2009, including information on building height and use (Hecht et al., 2013). Moreover, the number of buildings in OSM is steadily increasing. Compared to an OSM dataset of the same research area obtained two months before, the dataset used here contains already 7695 more (which corresponds to +4.7 %) building polygons. Not only completeness (in terms of the number of buildings) but also the number of tags assigned in rural areas in the study area is considerably lower. Properties such as the building height or the number of floors are mainly available in the urban part of the study area. About 82 % of the buildings are only marked by the tag “building = yes” (OSM contributors, n.d.). To deal with this lack of information about building attributes, the layer can be intersected with land-use data (Alhamwi et al., 2017). In the current version of the method presented here, the attribute “land use” from the ALKIS dataset is also utilized to categorize buildings. In cases where even this information is not available, the category “residential buildings” is chosen, which applies to 0.6 % of the buildings, mostly in rural areas. In this way, the algorithm classifies all buildings reliably into wastewater categories. At the same time, however, agricultural buildings in rural areas – stables, halls, etc. – are wrongly identified as residential buildings, when OSM tags are missing. As a result, the disaggregation of the population per municipality distributes the inhabitants among too many houses. The classification process could be

(a) (b)

Figure 4.6.: Comparison of data completeness regarding buildings:
(a) OSM data; no buildings have yet been mapped in the western village (marked by the dashed line).
(b) Digital topographic web map of the same villages from the WMS WebAtlasDE/MV (LAiV, n.d.-b).

improved by similarity measurements of building footprints, e.g., as described by Fan et al. (2014a), or by interpreting buildings and related "points of interest" (Fonte et al., 2015).

Determination of the inflow target value

A critical point of the method is to find suitable target values for the calibration of the discharge rates q_R, q_I, and q_C. In the approach presented here, daily measurements of wastewater inflow to treatment plants and pumping stations are used. Since the volume of domestic and commercial wastewater is subject to daily fluctuations, the absolute minimum cannot be the target value. In this study, dry weather inflow is assumed if rainfall on the day itself and on the previous day is below $0.1\,\mathrm{mm\,d^{-1}}$. Figure 6 shows the inflow to a pumping station at such conditions. In the periods from July 2017 to September 2017 and October 2017 to February 2018, high precipitation is recorded, which is the cause of higher water inflows to sewage treatment plants and pumping stations (see Figure 4.7). In general, the year 2017 can be classified as high in precipitation with 739 mm compared to the long-term average of 616 mm (1981–2010, calculated by precipitation data from the German national meteorological service (DWD)(DWD, n.d.-a)). Presumably, due to the finely branched Rostock sewage network, which extends from the urban area to the suburbs and surrounding villages, rainfall events that occurred more than two days before are wrongly detected as dry weather inflow. Additionally, unavoidable infiltration of stormwater into separate drainage systems leads to higher inflows. Groundwater infiltration is likely to occur, as groundwater levels are generally high in many parts of the study area. Another issue that has to be considered here is extraneous water and snowmelt infiltration into the sewer system (Cahoon & Hanke, 2017). This is the case in March 2018 to April 2018. The mean value of the dry weather runoff is increased by such events and is therefore unsuitable as a target inflow value. To take the mentioned conditions into account, the first quartile of the dry weather inflow at sewage treatment plants and pumping stations is chosen as the target value. Other target values and approaches to determine them may be more suitable for other study areas. For example, wastewater volumes can be compared to drinking water intake in a first step. This can be used to exclude inflow values influenced by rainfall infiltration. Alternatively, hydrograph separation could be used to distinguish between wastewater flows and stormwater flows (Pellerin et al., 2007). Where seasonal changes in wastewater inflow are high, the selection of separate target values for optimization for each season might be beneficial. To avoid misinterpretation of seasonal changes caused by single extreme events, the evaluation of time series longer than two years is recommended.

Parameter optimizing process

The two optimization methods result in similar parameter combinations, both for the optimization on the basis of the wastewater treatment plant inflows and the pumping station inflows. Since the catchment areas of the pumping stations are mostly located in the urban area and those of the sewage treatment plants (with the exception of the central sewage treatment plant Rostock) cover the rather rural area, differences in the optimized parameters q_R, q_I, and q_C (cf. Table 4.2) can be attributed to settlement structural conditions. The estimated amount of wastewater, q_R, per inhabitant for parameter optimization is between 61.5 and 93.6 L/d, depending on the optimization method and the target values considered. The lower values are obtained for rural areas. As residential use is the main source of wastewater in the study area and the per capita volume of wastewater of 93 L/d matches the average drinking water consumption of 93.8 L/(person d) indicated by the WWAV in 2017 (WWAV, 2019), the parameter set optimized for the entire study area is chosen for further calculations:

- $q_\mathrm{R} = 93.0\,\mathrm{L\,person^{-1}d^{-1}}$;
- $q_\mathrm{C} = 2.4\,\mathrm{L\,m^{-2}\,d^{-1}}$;
- $q_\mathrm{I} = 0.6\,\mathrm{L\,m^{-2}\,d^{-1}}$;

The optimized parameter, q_C, for commercial buildings varies between 2.4 and $3.1\,\mathrm{L\,m^{-2}\,d^{-1}}$. For industrial buildings, the optimization result

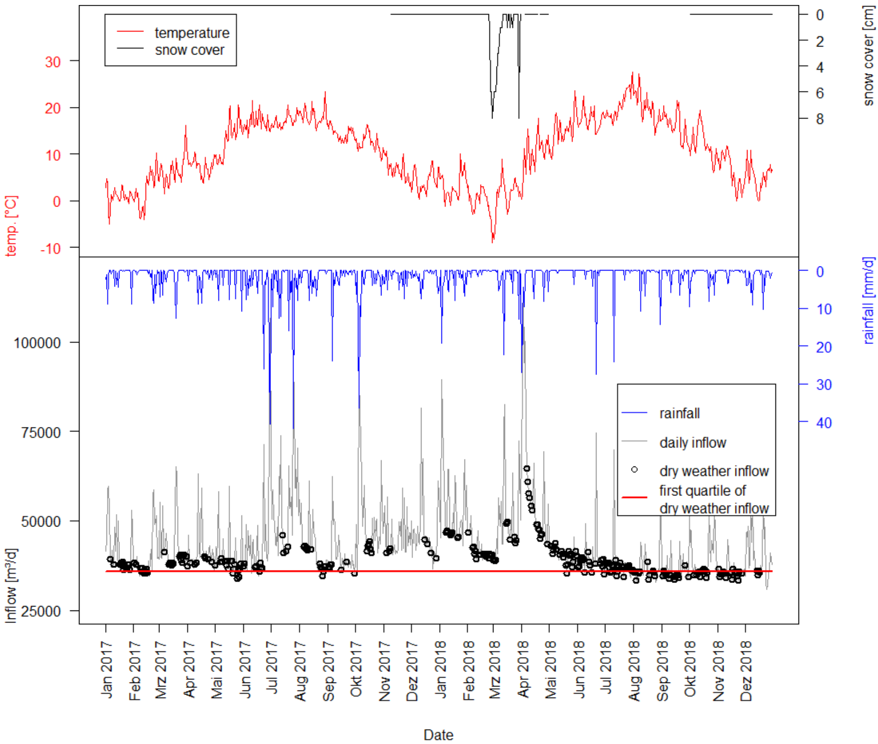


Figure 4.7.: Weather data and inflow data used to derive target values. Upper part: temperature and snow cover, measured by DWD in Rostock–Warnemünde (DWD, n.d.-a)
Lower Part: inflows to the central WWTP of Rostock in general and at dry weather conditions; the red line (first quartile) is the selected target value for optimization at this WWTP.

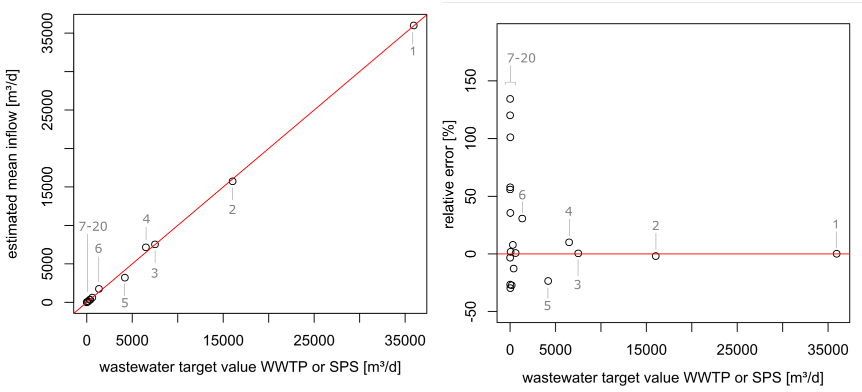
Table 4.2.: Result of the parameter optimizing process.

Optimization Method	$\mathbf{q}_{\mathrm{R}}$ L person^{-1}d^{-1}	$\mathbf{q}_{\mathrm{C}}$ L m^{-2} d^{-1}	$\mathbf{q}_{\mathrm{I}}$ L m^{-2} d^{-1}	**Area**
Linear regression	80.1	2.7	1.5	WWTPs without central WWTP
Nelder–Mead	61.5	3.1	2.9	Rostock/ mainly rural area
Linear regression	93.6	2.4	0.6	Pumping stations/mainly
Nelder–Mead	93.6	2.4	0.6	urban areas
Linear regression	93.0	2.4	0.6	WWTPs including the central
Nelder–Mead	93.1	2.4	0.6	WWTP Rostock (entire study area)

of the parameter qI is 0.6 to 2.9 L m^{-2} d^{-1}. Both q_{C}, and q_{I}, are higher in the rural part of the study area. These findings are explained by the classification process (cf. Figure 4.2, step 1). The algorithm identifies large production halls with presumably low wastewater output as industrial buildings in the urban area of Rostock, while agricultural buildings with presumably higher wastewater output (e.g., stables) are classified as "industrial" in rural areas. Accordingly, the actual amount of wastewater per m^2 in rural industrial buildings would also be higher than in urban industrial buildings (e.g., production halls), which is reflected in a higher optimized q_I. Although a part of the drinking water in rural areas is not returned to the sewage network (e.g., for the irrigation of plants in gardens and dwellings) 61.5 L person^{-1}d^{-1} is too low, compared to the average consumption. There are several possible explanations for the low q_{R} value in rural areas. The effect of missing or incorrectly assigned buildings in the OSM dataset, as well as the effect of commuting, has to be considered. A large proportion of the rural population's wastewater may be produced at the workplace in urban areas, so an adjustment of f_{R} is needed. In addition, with this factor, the settlement structure of different localities within a municipality is not taken into account so far. A small village with residential development next to a larger village with business parks (and accordingly jobs) in the same municipally is therefore evaluated equally. Here, further work is needed to establish parameters which can better represent this heterogeneity.

Calculated wastewater volume

The comparison of the calculated wastewater inflow with the daily values of dry weather inflow at SPSs and WWTPs shows that the method can generate realistic values mainly in urban areas (cf. Figure 4.8a, numbers 1–6). Here, the maximum relative error is 31 %. The estimated wastewater volume of the central WWTP of Rostock (number 1) is $35\,992\,\mathrm{m^3\,d^{-1}}$, which differs by 0.1 % from the target value of $35\,947\,\mathrm{m^3\,d^{-1}}$. Moreover, WWTPs in rural areas show relative errors less than 30 % if target inflows exceed $50\,\mathrm{m^3\,d^{-1}}$. The estimated volume at WWTP number 8 is $341\,\mathrm{m^3\,d^{-1}}$, with $391\,\mathrm{m^3\,d^{-1}}$ set as the expected value. WWTPs with a target inflow smaller than $50\,\mathrm{m^3\,d^{-1}}$ can have large relative errors. For example, the estimated quantity of $14\,\mathrm{m^3\,d^{-1}}$ at sewage treatment plant number 17 is more than twice the estimated value of $6\,\mathrm{m^3\,d^{-1}}$. An overview about all values is provided in Table 4.3. It must be borne in mind that the target value (1st quartile of dry weather inflow) is a parameter defined ad hoc which represents an assumption about the true average inflow in dry weather. In addition, the calculation with a single set of mean discharge rates q_R, q_C, and q_I cannot reflect the individual use of a specific building. For example, individual behavior of water consumption will lead to overestimations or underestimations if catchments are small. Furthermore, in sewage treatment plants with a smaller catchment area in rural areas, only a few missing or incorrectly allocated buildings have a negative effect on the calculated result. Hence, the relative error related to the target value is smaller, the larger the catchment area of the sewage treatment plant or pumping station (cf. Figure 4.8b). Using disaggregation procedures as an example, Schiller and Bräuer (2013) also argue that the individual error is greater the higher the level of detail. In the case of values generated on a building level, the error range is largest. The



(a) (b)

Figure 4.8.: Comparison of estimated wastewater inflows and target values:
(a) Absolute inflows to wastewater treatment plants and pumping stations, numbers of SPSs and WWTPs (gray) refer to Figure 4.1 and Table A.2.
(b) Relative error related to the inflow target value.

Table 4.3.: Comparison of estimated wastewater inflows and target values: Q_{target} = wastewater target value, Q_{gen} = generated wastewater inflow by OSM buildings, Err = absolute error; Rel. Err = relative error.

N	$\mathbf{Q_{target}}$ ($m^3\,d^{-1}$)	$\mathbf{Q_{gen}}$ ($m^3\,d^{-1}$)	**Err** ($m^3\,d^{-1}$)	**Rel. Err** (%)
1	35,947	35,992	45	0.1
2	16,034	15,734	-300	-1.9
3	7501	7537	36	0.5
4	6498	7153	655	10.0
5	4189	3206	-983	-23.5
6	1338	1748	410	30.7
7	612	617	5	0.8
8	391	341	-50	-12.7
9	306	330	24	7.8
10	176	128	-48	-27.2
11	57	58	1	1.8
12	28	20	-8	-29.6
13	26	52	26	101.1
14	26	35	9	35.5
15	13	10	-3	-26.6
16	10	16	6	57.8
17	6	14	8	134.4
18	4	9	5	120.2
19	3	4	-1	-3.3
20	4	5	1	55.9

calculated result should therefore be aggregated on the largest possible reference level according to the planning task. For the drainage planning, the mentioned study proposes the level of districts or “solitary settlement units”. In the application example described here, the spatial resolution of LUPs is chosen, which corresponds the proposed aggregation level by Schiller and Bräuer (2013).

Application examples LUP and urban wastewater management

As described in section 4.1.2, yield factors for every type of land use in LUP are derived by a spatial join and aggregation process, using QGIS. The combination of land-use types and wastewater discharges enables illustrating the effect of land-use change in modeling future scenarios. The largest wastewater yield factors (Figure 4.9 are related to the LUP types “areas for public facilities” and “core development areas” and (medians: 0.14 to $0.22\,\mathrm{L\,s^{-1}\,ha^{-1}}$). Industrial parks, mixed building areas, residential areas, and special building areas are in the middle range of yield factors (medians: 0.05 to $0.07\,\mathrm{L\,s^{-1}\,ha^{-1}}$). In the work of Willuweit and O’Sullivan (2013), three land-use types are distinguished in the urban area of the Dublin region: For “medium dense to continuous dense urban fabric/commercial”, a value of 0.48 to $0.50\,\mathrm{L\,s^{-1}\,ha^{-1}}$ is estimated. For the category “sparse and discontinuous urban fabric/residential”, 0.14 to $0.16\,\mathrm{L\,s^{-1}\,ha^{-1}}$ is calculated, and 0.10 to $0.14\,\mathrm{L\,s^{-1}\,ha^{-1}}$ for cells of the land-use type “industrial”. Compared to the region of Rostock, the higher values cited here presumably result from a higher per capita water use. The water demand of the population of approximately 1.5 million in the Dublin Region Water Supply Area is $550 \times 10^6\,\mathrm{L\,d^{-1}}$ which corresponds to $367\,\mathrm{L\,person^{-1}}d{-}1$. The DWA worksheet A 118 (DWA, 2020c) recommends using 0.2 to $0.5\,\mathrm{L\,s^{-1}\,ha^{-1}}$ for choosing the component size of sewer networks in commercial and industrial areas for companies with low water consumption and up to $1.0\,\mathrm{L\,s^{-1}\,ha^{-1}}$ for companies with medium to high water consumption, referring to the catchment area connected to the sewage system. These values are higher than the calculated ones (see Figure 4.9), as they represent an (hourly) maximum instead of daily mean values. However, deriving the variability of wastewater discharge from OSM data or other VGI could

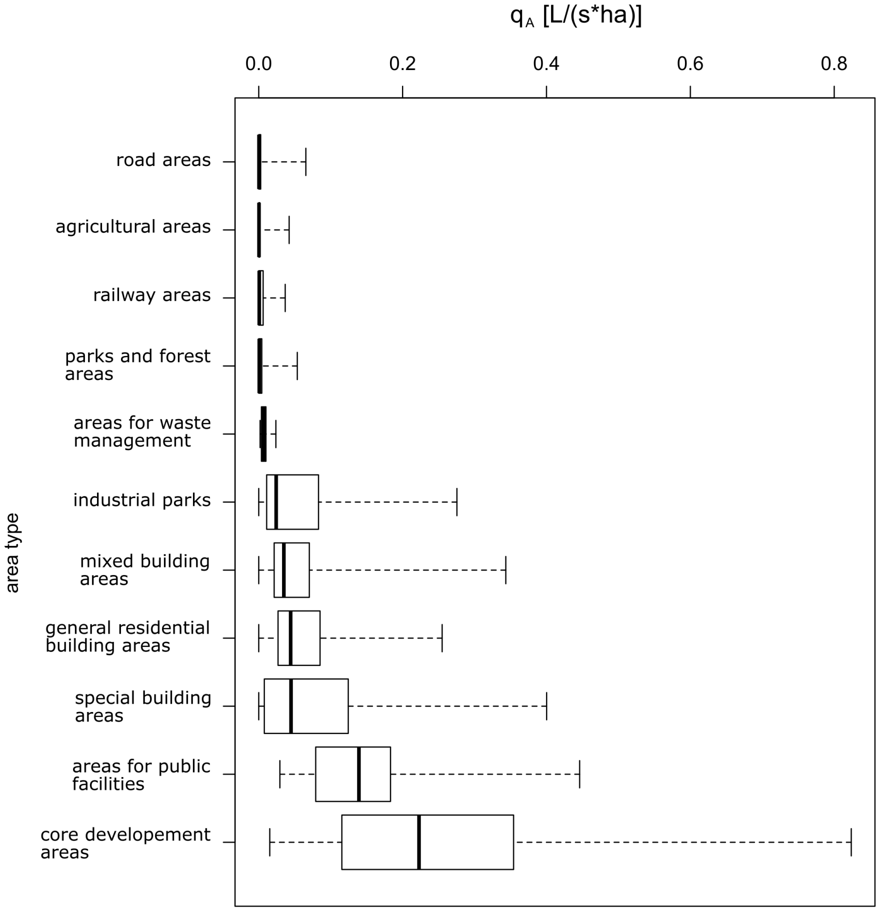


Figure 4.9.: Boxplots of wastewater yield factors for typical categories of a LUP.

be a subject of future research.
In Figure 4.9, wastewater is also "produced" on road areas, agricultural areas, park and forest areas, and areas for waste management. This can be due to incorrectly classified buildings or inaccurately drawn LUP areas. On the other hand, e.g., road areas actually contribute to the volume of wastewater, as tram depots or ticket counters are located in these areas.
The GIS-based approach to accumulate generated wastewater along a sewer network allows the estimation of the actual flows (see Figure 4.10). With the same approach, wastewater flows can be represented in future urban and regional planning variants. Possible applications are decision support systems for the construction or reconstruction of drainage systems on a conceptual level. In the rural structured part of the study area, phosphate inputs from wastewater treatment plants into rivers are investigated (Tränckner et al., 2019). When merging decentralized small wastewater systems into a central system, it is worth considering a fourth treatment stage to reduce the input via the treated wastewater. In order to determine the technological optimization potential, the amount of wastewater to be treated is the central data basis, in addition to the sewer system itself and equipment of the wastewater treatment plants.
On the other hand, especially in developing countries, the construction and maintenance of large sewerage networks and cost-effective wastewater treatment are a challenge. With the help of spatially differentiated wastewater data, decentralized wastewater concepts can be created in addition to existing systems, which enable the wastewater treatment and reuse close to the source (Singh et al., 2019).

4.1.4. Conclusion

The method introduced here represents an instrument to estimate discharges of wastewater from domestic, commercial, and industrial use on a high spatial resolution. The approach adds a new application for VGI to the existing methods. Using OSM as the main data source makes the method transferable to other regions. Where quality issues

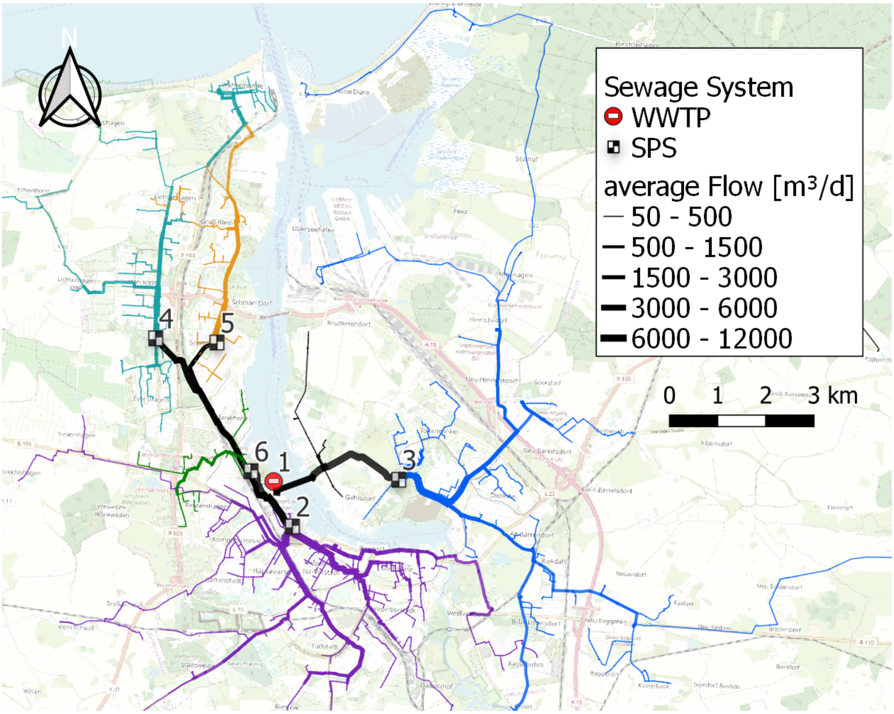


Figure 4.10.: Accumulated flow in the center of Rostock (main pipes; for clarity, only estimated flows $> 50\,\mathrm{m}^3\,\mathrm{d}^{-1}$ are shown); colors indicate different catchments of SPSs; background map: OSM ©OSM contributors.

of OSM building data generate uncertainty, especially in rural regions, additional data from different sources, e.g., authoritative data, may be used to identify missing buildings. To achieve higher accuracy in the classification process, OSM buildings data could be enhanced with POI from OSM, or an analysis of shape and size of building footprints could be applied.

For the calibration of the discharge rates q_{R}, q_{I}, and q_{C}, finding suitable target values is an essential step. Extraneous water, such as groundwater infiltration through leakages and rainwater or snowmelt infiltration into the sewage system, leads to temporarily high discharge rates, which increase the difficulty of finding a target value for the inflow. As this is a crucial step of the method, different approaches for the determination should be tested in future research, e.g., hydrograph separation or calibration with consumption rates of drinking water. Where long-term series of inflow to WWTPs and SPSs are available, the variability of wastewater discharges can be estimated by minimum and maximum values for different spaces of time. Seasonally varying target values derived in this way could improve the accuracy of the results, especially for small catchment areas of WWTPs. The method shown here, which uses one target value per WWTP or SPS, can be applied when inflow data sources are limited.

Wastewater discharges aggregated along the sewer networks in the study area generate realistic inflows to WWTPs and SPSs, which differ by a maximum of 31 % from the target inflow when this value exceeds $50\,\mathrm{m}^3\,\mathrm{d}^{-1}$. In small catchments, individual behavior of water consumption may lead to overestimates or underestimations. Here, the integration of peak factors to represent variability of wastewater discharges could improve the estimation. The estimated values cannot replace time-consuming measurements. However, the method can fill the gap of input data for model-building and urban water management, especially for research purposes, when measured data do not exist or their availability is legally restricted. By intersection of discharges with land-use plans, wastewater yield factors are derived as a scenario-capable tool, which enables us to simulate the effect of land-use change in modeling future scenarios.

4.2. Generate_SWMM_inp: An Open-Source QGIS Plugin to Import and Export Model Input Files for SWMM

4.2.1. Introduction

The SWMM developed by the US Environmental Protection Agency is a well-established software in the field of urban drainage modeling. It includes a hydrologic model for rainfall-runoff simulations and a dynamic hydraulic model for routing along a watercourse or drainage system (Rossman & Simon, 2022). Since its first version in 1971, scientists and practitioners have continuously enhanced the source code, which is mainly written in C since version 5 (Rossman et al., 2004). As SWMM is available as open source software (Simon & Tryby, 2018), users can edit the code to add new features and algorithms, which makes the software suitable for educational purposes and experimental studies. It has been used for numerous research projects and practical applications (Niazi et al., 2017). Among these are studies in the field of sanitary environmental engineering, such as the design of drainage systems (Lowe, 2010; Peng et al., 2020) including low impact development (LID) structures (Burszta-Adamiak & Mrowiec, 2013; Krebs et al., 2016), as well as river system models for flooding predictions (Rai et al., 2016) or for the assessment of impacts of urbanization scenarios (Jang et al., 2007; Kachholz & Tränckner, 2021), and water quality models (Tu & Smith, 2018).

To set up the sewer network model or watercourse model, SWMM needs a system of nodes, links and subcatchment areas. Nodes represent, for example, manholes, outlets or storage objects. Links can be pipes, watercourse sections, weirs or orifices. Specific properties of objects and settings are described by curves such as cross sections, pump curves and storage curves which are linked to the objects via unique identifiers. Rainfall intensities and dry weather inflows to nodes (i.e., wastewater inflows in a sewage network or base flows in rivers) are added to the model in the form of tabular time series and patterns. In the standard open-source version of SWMM, the data input can be performed in two

ways: Objects can be drawn or edited manually in the GUI; alternatively, all data can be imported as a text file called "input file" with the file extension ".inp" (Rossman & Simon, 2022). The latter option is the standard for all larger systems.
The required data about catchments, river systems, sewer networks and further water infrastructure are usually available as drawings for computer-aided design (CAD) software or as geospatial data ("geodata") (Rossman & Simon, 2022), including vector data as well as raster data such as DEM. So far, SWMM does not offer a direct import function for such files. The integration of geodata processing and SWMM model control is mainly included in commercial and proprietary variants of SWMM (e.g., PCSWMM (CHI, n.d.) with a ArGIS-like graphical user interface, InfoSWMM (Innovyze, n.d.) or GeoSWMM (Streams Tech Inc., n.d.)). Another commercial and closed-source tool is the "Lago Toolbox" with a GUI to generate SWMM input files, which is limited to 20 nodes and links in its free version and can only convert shapefiles (Lago Consulting, n.d.).
Hence, the typical workflow starts with the preprocessing of spatial data in a GIS environment. Numerous studies describing suitable GIS methods can be found. For example, catchments and subcatchments can be defined by aggregating, intersecting and spatially joining official data such as parcels in cadastral maps or land use surveys, or by DEM-based subcatchment delineation. The parametrization of subcatchments, e.g., calculation of terrain roughness, slope, width and depression losses from DEMs can be performed with GIS tools (Lee et al., 2018; Rai et al., 2016; Sadeghi et al., 2022). The share of impervious surfaces can be derived from aerial photographs and cadastral data. Parameters needed for modeling infiltration and groundwater flow can be obtained using soil maps and spatially located information from boreholes (Kachholz & Tränckner, 2021). Spatial queries in GIS can be used to allocate areas to receiving nodes. Advanced GIS methods for model parametrization of ungauged urban catchments with LIDs have been presented by Krebs et al. (2016). Yang et al. (2018) proposed a GIS-based approach for the generalization of storm sewer networks. Tu and Smith (2018) used land use data and aerial photography to derive pollutant build-

up and wash-off parameters. For studies in which data availability is limited, Blumensaat et al. (2012) developed an algorithm to set up a hydraulic sewer model based on freely available DEMs, street networks and OpenStreetMap data in GIS. Their approach included a GIS-based surface flow accumulation along a DEM with road information carved into the grid in order to generate a flow path network and connected catchments. Additionally, they estimated network dimensions by using the total catchment area, housing information from OSM and standard rainfall intensities.

The prepared geodata must then be converted into text strings for the SWMM input file, e.g., via "copy-and-paste" using a text editor or with scripts in programming languages such as R (R Developement Core Team, 2011) or Python (Python Software Foundation, n.d.). For the latter, several libraries are available to facilitate this process. For instance, for the R programming language, the swmmr library (Leutnant et al., 2019) offers tools to read and write SWMM files (input, output and report files) and facilitate model data management. Comparable functions for Python are provided by the swmm_api package (Pichler, 2022). PySWMM is a Python interfacing wrapper to SWMM which enables the interaction with the model during a simulation (McDonnell et al., 2020). The Python package swmmio (Erispaha, 2022) allows the modeller to change data in existing input files in order to run altered models for the comparison of scenarios or sensitivity analysis. Tools for the access and visualization of model results, stored in a binary output file (".out"), are provided by the swmmtoolbox package (Cera, 2025). Kachholz and Tränckner (2021) demonstrated the use of Microsoft Excel with its Visual Basic for Applications (VBA) programming interface to set up SWMM models with parameterized geodata. Especially for the development of real-time control strategies with SWMM algorithms, MatSWMM 5.1.012 by Riaño-Briceño et al. is an open-source software package written for Matlab, Python and LabView (Riaño-Briceño et al., 2016). However, the application of these packages and scripts requires basic programming skills for the input via command-line interfaces or integrated development environments.

An alternative approach is the integration of or connection with SWMM in an existing GIS environment. This idea was realized for the ArcGIS environment by Shamsi and Smith (2005) and Lee et al. (2020), but the application of their software is limited to users with a license for the closed-source GIS. QGIS, by contrast, is an open-source GIS with programming interfaces in Python and R, which allow the users to create their own tools QGIS project (2024). New tools and collections of tools can be shared with other users as so-called plugins. QGEP, for example, is a wastewater management plugin, which is maintained by the Swiss user group of QGIS. Its data structure, based on the data model standard “VSA-DSS” of the Swiss Wastewater Association VSA, is implemented in a PostgreSQL database with PostGIS. The plugin is able to create an input file, run SWMM and read the results of the simulation (The QGEP Project, 2021). GISWATER is another open-source application that can be integrated in QGIS as a plugin. Again, the water infrastructure data are managed in a PostgreSQL database system with PostGIS. The plugin provides a variety of tools with a complex user interface including import and export functions to SWMM and EPANET (Giswater, n.d.). A common challenge with these all-in-one solutions, especially for first-time users, is the initial setup of the database systems and file structures. Simple export/import tools in QGIS, as for other modelling software (RiverGIS for HEC-RAS (Cimpianu & Mihu-Pintilie, 2019), TUFLOW Plugin (Tuflow, n.d.), or QEPANET (Menapace et al., 2019) for EPANET), are to date not available for SWMM (Sadeghi et al., 2022).

4.2.2. Concept and implementation of a QGIS plugin as an interface between GIS and SWMM

To address the mentioned challenges, our goal was to develop an open-source QGIS plugin that enables the direct transfer of geodata and tabular characteristic curves or time series into an input file and conversely, to read out existing SWMM input files into editable data structures. The concept of the plugin is to allow data processing in the appropriate software solution (QGIS for geodata and, if necessary, EXCEL/LibreOffice Calc for tables). The column names of the attribute tables are derived from the names, which would be automatically generated in the input file by SWMM after saving a model. Thus, they are quite similar to those in the SWMM user interface, e.g., the columns “Elevation”, “MaxDepth”, “InitDepth”, “SurDepth”, “Aponded” in the junctions´ layer refer to “Invert El.”, “Max.Depth”, “Initial Depth”, “Surcharge Depth”, and “Ponded Area” in the corresponding input mask in SWMM. For a fast workflow, input masks of the tools are designed as simply as possible. The plugin is written in Python with a focus on fast processing of data in dictionaries and in table structures with the aid of the pandas package (Reback et al., 2022). The plugin “generate_swmm_inp” is made available in the official QGIS plugin repository (QGIS Project, n.d.-a). After installation with the plugin manager in QGIS, three tools are added to the toolbar.

The first tool, “1_GenerateDefaultData”, loads a default data set containing layers for basic SWMM objects. Default files are provided for both SWMM version 5.1 and SWMM version 5.2. The layers are added to the QGIS project with pre-defined symbols according to the style in the GUI of SWMM. Model options and further parameters are saved in tables in the same folder. An overview of default files for different SWMM objects and attributes is presented in Table A.3 and Table A.4 in Chapter A.

The second tool, “2_GenerateSwmmInpFile”, enables the user to create a SWMM input file directly from layers and tables within QGIS. In the input mask of the tool, the user chooses a file name for the resulting input file and selects the desired layers and tables (cf. Figure 4.11). The layers´ attributes are then translated into text strings for each section. This requires specific column names within the shapefiles and spreadsheet names within the tables. A warning is displayed if a required column is missing. The tool finally joins the corresponding sections to create the input file. With the third tool, “3_ImportInpFile”, input files for existing SWMM models can be imported into QGIS. The resulting layers can be saved in different formats (e.g., shapefile, geopackage or geojson). A user-defined prefix can be added to the imported files in order to distinguish between different models and layer versions.

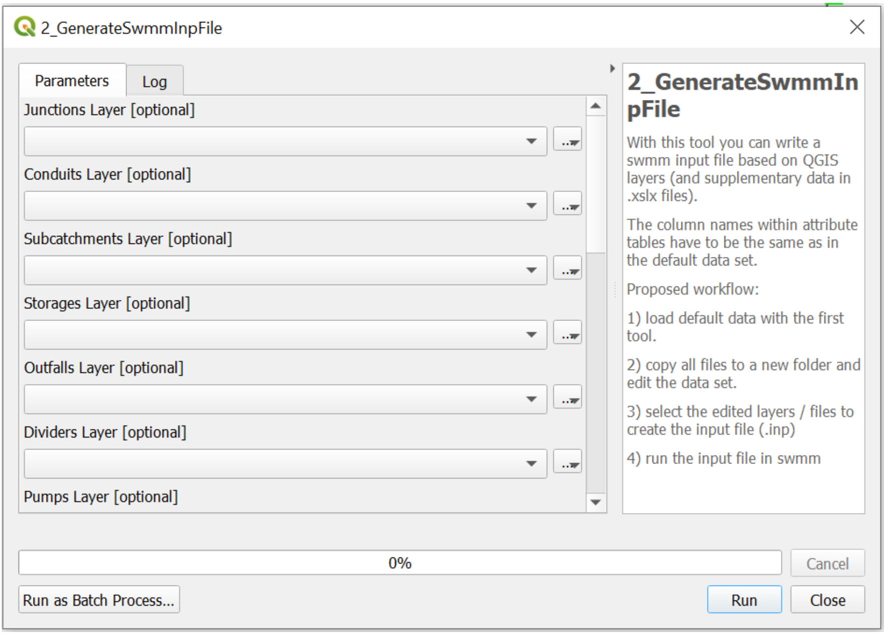


Figure 4.11.: User interface of the export tool

4.2.3. Application example

The workflow of the plugin in both directions is demonstrated for a subcatchment of the sewer system in Rostock. The city of Rostock is located in the northeast of Germany (cf. Figure 4.12a). Its sewage and stormwater network has a total length of about 1500 km. In the city center, a combined sewer system is operated, whereas in the surrounding districts and suburban areas a separate sewer system is prevalent (cf. Figure 4.12b). Combined sewer overflows, occurring during rainfall events, are conducted to the estuary of the Warnow river. For the application example, parts of the corresponding subcatchments shall be converted into a separate system, in order to mitigate combined sewer overflows. In this imaginary, so-called "future scenario", stormwater would have to be captured and retained or discharged separately into a

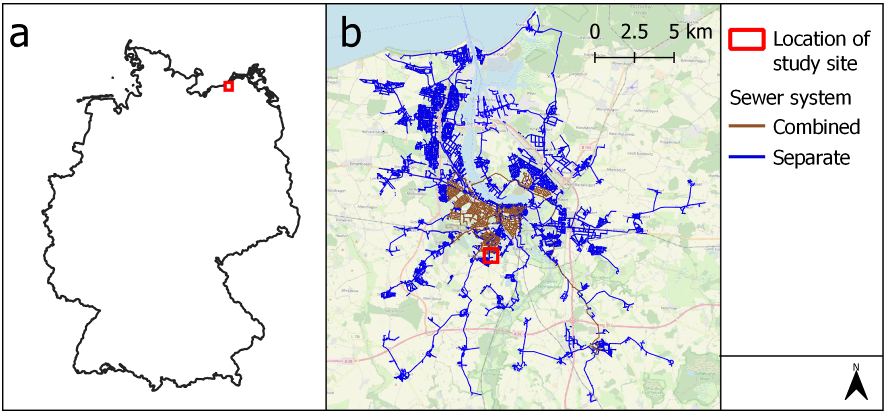


Figure 4.12.: Location of the study site: a) within Germany; (b) classification of the sewer system and location of the study site within the city of Rostock; background map: OSM ©OSM contributors.

watercourse.
To assess possible impacts of this conversion on both sewer system and discharge points, the aim of this application example is to:

1. characterize the subcatchments by geodata in QGIS;
2. use these values to set up a model in SWMM to estimate for rainfall events of different intensities:
   a) current discharge volumes;
   b) expected discharge volumes in future scenarios.

The exemplary study site is located next to the park "Kringelgrabenpark" in the south of Rostock. Surrounding areas are drained by both separate and combined sewer networks. A small open watercourse "Kringelgraben" runs through the park from west to east, where it starts to run through piped watercourse sections. There are two urban stormwater catchments with separate sewer systems (cf. Figure 4.13), whose stormwater runoff is discharged directly into the watercourse.

The stormwater catchments were named according to the name of the discharge permits of the outfalls ("WE_48" and "WE_55"). Adjacent parcels in the north of the study area are currently drained by the combined sewer system of the city (brownish area in Figure 4.13). As the detailed picture in Figure 4.13 shows, the sewer system crosses the street of catchment "WE_48", but the two catchments are not connected to each other. A storage unit in the combined sewer system throttles maximum flows towards the city centre.
For the imaginary model of the separate stormwater system in the "future scenario", it was assumed that the layout and pipe dimensions would be the same as the dimensions of the combined sewer system at present. The storage would stay in use and an outfall into the Kringelgraben would be placed behind it. This scenario is depicted in Figure 4.14. The new discharge point as well as the catchment are named "Var_Sep". Preprocessing of geodata was performed in QGIS version 3.22. Geodata for the sewer network (junctions, conduits, and pumping stations) were provided by the local wastewater asscociation "Warnow Wasser und Abwasserverband" WWAV in shapefile format. The sewer objects needed for the model in SWMM were selected with the aid of the routing algorithm of the plugin "WaterNetAnalyzer" (Schilling & Tränckner, 2020) and grouped in separate layers in QGIS. The attributes of each layer were then adjusted based on the default data set by using the standard QGIS tool "field calculator".
The catchment area boundaries and subcatchments were extracted from official cadastral datasets. Each subcatchment was connected to the nearest junction with a spatial join. Streets were further subdivided by Voronoi cells from junction points if multiple manholes were located within a street area. The mean slope was derived from DEM rasters with a grid size of 1 m^2. Subcatchment widths and areas were calculated from subcatchment geometries. Roughness and infiltration parameters were set by a spatial join according to previous models of the Kringelgraben catchment from Kachholz and Tränckner (2021), which were imported into QGIS with the tool "3_ImportInpFile" from the developed plugin. Landuse data of the same study and OpenStreetMap Geofabrik GmbH (n.d.-b) were used to derive the degree of imperviousness of

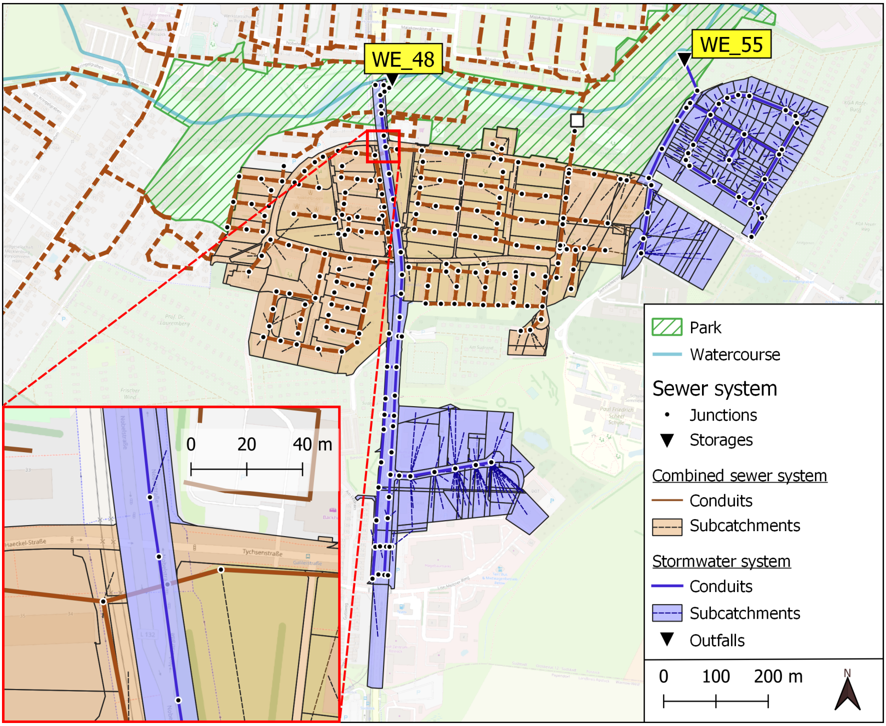


Figure 4.13.: Current drainage situation at the study site: stormwater catchment “WE_55”, stormwater catchment “WE_48” and adjacent combined sewer system; relevant subareas of the combined sewer system for this study are highlighted in brown; background map: OSM ©OSM contributors.

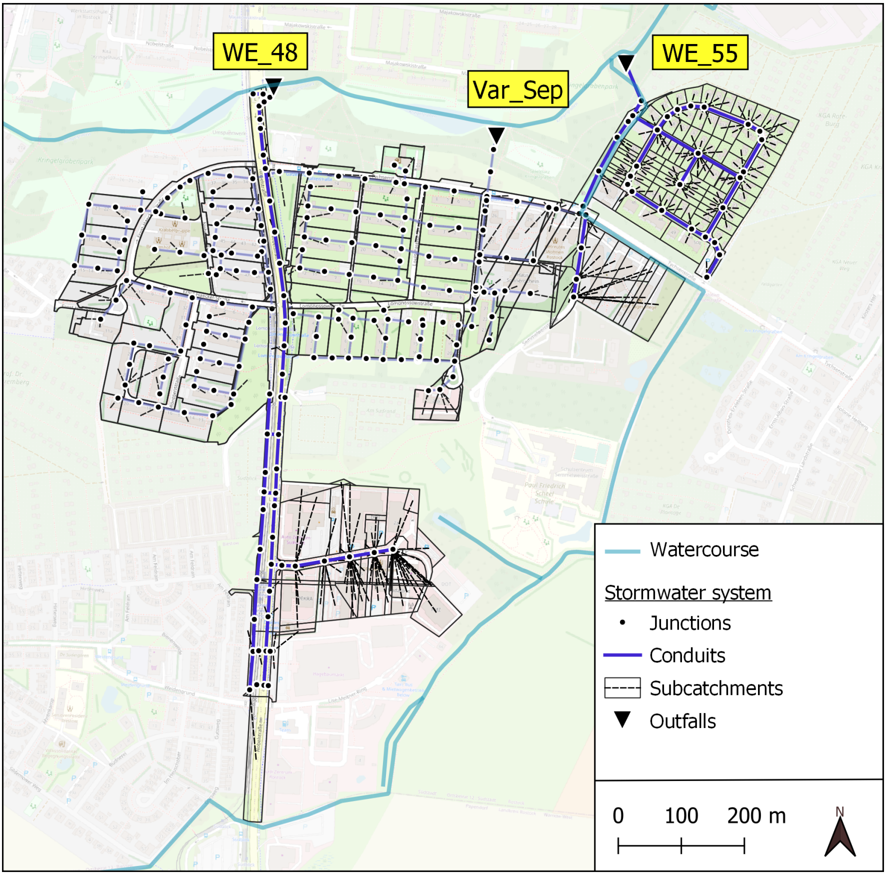


Figure 4.14.: Future scenario with three stormwater catchments; background map: OSM ©OSM contributors.

the subcatchments. The resulting summary for each subcatchment was prepared using the QGIS field calculator to generate mean, maximum and minimum values.

Rainfall data and model setup

Synthetic rainfall time series for the model were generated in Microsoft Excel by transferring statistic block rains (provided by the German Weather Service) into dynamic model rains as described by Kachholz and Tränckner (2021). Three rainfall events were applied in the models with a return period of 1 year and duration times of 15 min, 1 h and 2 h. Simulations were executed with SWMM version 5.1.015 with a dynamic wave routing model. The total simulation time was set to 6 h, with a routing step of 10 s. The Green-Amp method was used for the infiltration model for all subcatchments. With the tool “2_GenerateSwmmInpFile”, the prepared layers in QGIS and tables for rainfall data and model options were merged into an input file for SWMM.

Results and Discussion

The GIS analysis carried out in advance shows that the three catchments of the study site differ in several properties that are relevant to water management. Table 4.4 summarizes main characteristic values for each site. “WE_55” is a residential area of 8.3 ha with mainly detached houses. Approximately 59 % of its area is pervious as many houses are surrounded by gardens. By contrast, the catchment “WE_48” is characterized by a commercial area in the south and a major road that connects the commercial area with the city and represents an important transport axis in the southern direction. Impervious surfaces cover approximately 78 % of the catchment. The future stormwater catchment “Var_Sep” would be another residential area of 24.1 ha covered with blocks of houses and larger green areas in between. In this model, the conversion of the current combined sewer system into a separate system would likely have a remarkable impact in this section of the watercourse. Total discharge volumes would increase by 88 % (event “15min_1y”), 77 % (event “1h_1y”) and 77 % (event “2h_1y”). Likewise, peak inflows

Table 4.4.: Characteristic numbers of the exemplary study sites.

Catchment	**WE_48**	**WE_55**	**Var_Sep**	**Base data in QGIS**
Catchment properties				
Total area (ha)	8.9	8.3	24.1	Cadastral data (polygons)
Number of subcatchments	85	118	121	
Mean impervious area (%)	78	39	32	Landuse data, OSM
Slope (%) (min, max, mean)	0.9, 16.9, 3.4	2.8, 15.0, 5.7	31.1, 23.0, 4.6	DEM
Sewer system properties				
Number of conduits	51	33	176	
Total conduit length (m)	1743	1331	5525	Sewer network (lines)
Longest flow path (m)	986	474	1057	
Manning roughness of conduits ($\mathrm{s\,m^{-1/3}}$)	0.015	0.015	0.015	Imported model data
Number of junctions and outfalls	52	34	180	Sewer network (lines)

Table 4.5.: Model results for the simulated rainfall events.

Catchment	WE_48	WE_55	Var_Sep
Rainfall event		**15min_1y**	
Total precepetation (mm)		9.57	
Total discharge volume at outfall (m^3)	514	171	608
Peak inflow ($m^3\,s^{-1}$)	0.574	0.250	0.359
Rainfall event		**1h_1y**	
Total precepetation (mm)		15.39	
Total discharge volume at outfall (m^3)	889	293	906
Peak inflow ($m^3\,s^{-1}$)	0.648	0.263	0.366
Rainfall event		**2h_1y**	
Total precepetation (mm)		18.24	
Total discharge volume at outfall (m^3)	1077	354	1095
Peak inflow ($m^3\,s^{-1}$)	0.678	0.287	0.365

of $0.359\,m^3\,s^{-1}$ (“15min_1y”), $0.366\,m^3\,s^{-1}$ (“1h_1y”) and $0.365\,m^3\,s^{-1}$ (“2h_1y”) from “Var_Sep” would affect the flow regime of the Kringelgraben (cf. Table 4.5). Moreover, in comparison to “WE_48” and “WE_55”, peak stormwater discharges from catchment “Var_sep” continue for a longer time after a rain event (cf. Figures 4.15 to 4.17).

Since this model represents a fictitious scenario in which the model parameters were derived from existing models without further calibration, the uncertainty of the results cannot be quantified. The example, however, shows that the tools of the plugin allow a user-friendly and systematic construction of SWMM models by open-source software based on geodata from various sources. The variety of data formats that can be imported by QGIS expands the amount of information that can di-

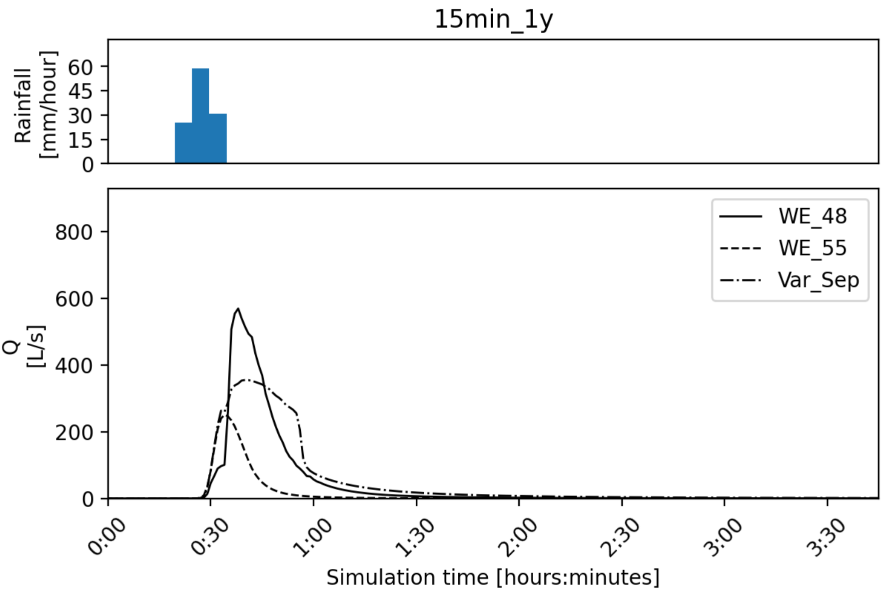


Figure 4.15.: Model rainfall intensity (duration = 15 min, return period = 1 year) and flow (Q) at discharge points

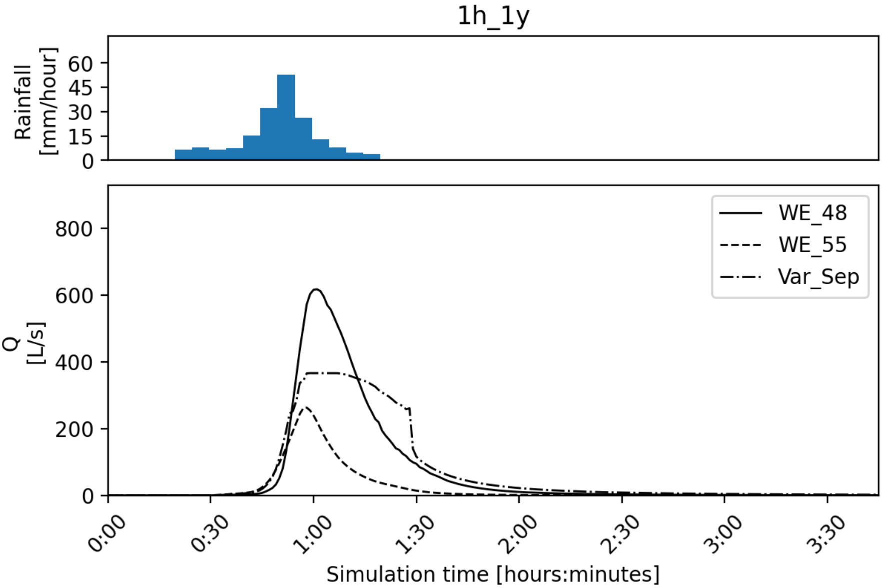


Figure 4.16.: Model rainfall intensity (duration = 1 h, return period = 1 year) and flow (Q) at discharge points

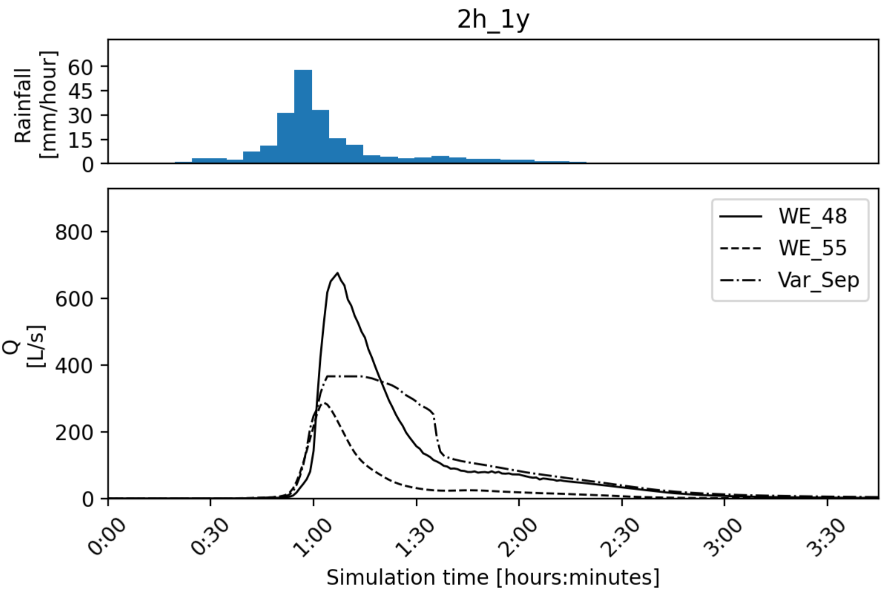


Figure 4.17.: Model rainfall intensity (duration = 2 h, return period = 1 year) and flow (Q) at discharge points

rectly be used for the model setup (QGIS project, 2024). As the main advantage of the plugin, the tool "2_GenerateSwmmInpFile" simplifies the former time-consuming data transfer from QGIS to SWMM, which was mentioned for example by Sadeghi et al. (2022). Since individual layers can be selected for export with this tool, it is possible to build model variants from different layer combinations. For example, subcatchments and sewer networks with different levels of detail can be used, as proposed by Krebs et al. (2016) and Yang et al. (2018), or design variants of a sewer network with different routes and pipe dimensions.

The import function ("3_ImportInpFile") of the plugin facilitates the editing process of existing models and enables them to be conveniently integrated into new models. As shown in the application example, model parameters such as catchment properties can be transferred by spatial queries in GIS to create a submodel for particular case scenarios. Moreover, importing models and creating partial models or simplified models in GIS could be used to reduce the computation time (Yang et al., 2018). The import function also extends user possibilities to gather additional information when data availability or accessibility is limited, e.g., as described by Blumensaat et al. (2012).

So far, the functions of the plugin "generate_swmm_inp" are limited to the import and export of geodata and tables for model preparation. Several features in SWMM such as settings regarding climate-related variables still have to be manged manually in SWMM. Model results can be saved as a text file within the SWMM user interface. The extraction of model results from SWMM output files, e.g., as it is possible using python scripts with packages such as swmm-api (Pichler, 2022) or swmmtoolbox (Cera, 2025), is not yet implemented in the plugin. However, the combination of direct manipulation of the base data with the QGIS toolbox and the translation of these data into models for SWMM already fills a large gap in the functionality of the SWMM user interface (Sadeghi et al., 2022).

4.2.4. Conclusions

This article describes the goals and functions of the plugin "generate_swmm_inp" for QGIS, which serves as an interface between the GIS environment and SWMM. The plugin considerably simplifies the workflow from the preparation of geodata to the model. Different from the aforementioned solutions (Erispaha, 2022; Leutnant et al., 2019; McDonnell et al., 2020; Pichler, 2022) SWMM input files can be created without the need for any programming knowledge. A challenge for first time users is to arrange their own data according to the specific column names required for the creation of the input file. Therefore, using the default data set as a template, which can be added to a QGIS project with a few clicks, is recommended. Further case studies are currently being conducted to test the deeper application of the tools. Users are invited to share their experience in the public code repository [1] and to participate in the future development of the open-source software.

[1] The sourcecode is avialable with a GPLv2.0 license at the GitHub page of the author: https://github.com/Jannik-Schilling/generate_swmm_inp

5. OSWeGe: Capacity building through GIS training

The term “capacity building” refers to the ability of a stakeholder, organization, authority, etc. to fulfil its functions, solve problems and achieve its goals (Alaerts & Kaspersma, 2022). Capacity building thus includes resources in the form of technical knowledge and skills, time and personnel, infrastructure, tools and goods, as well as networks with others in order to benefit from their capacities. Depending on the addressed challenge, different aspects are emphasized. For example, Engle and Lemos (2010) explore how governance mechanisms contribute to adaptive capacity in river basin management whereas Alaerts and Kaspersma (2022) highlight learning, knowledge generation and sharing within institutions.

However these advantages and possibilities of open source and open data are not used sufficiently (cf. Borowski & Hare, 2006; Weke et al., 2024a). The reasons depend on the type of stakeholder and their specific framework conditions. For example, in the field of river management, local authorities (agencies, associations) are generally responsible and must hire qualified personnel for this task. However, it is challenging to establish the required expertise, particularly at the local or regional level, partly due to limited financial or temporal resources (Arvidsson et al., 2022). River management tasks have therefore frequently been outsourced to external service providers in the past, a practice which lead to a loss of expertise or “capacity”.

As shown in section 3.2, part of the challenges in river management are linked to spatial aspects, mainly due to the hierarchical structure of subcatchments and river networks (upstream to downstream). The application examples and case studies cited in section 3.4.1 demonstrate that GIS is a pivotal instrument in river management. Therefore, the

following section addresses the potential of open source GIS training to contributing to the capacity of staff from WBV There are various dimensions of capacity building which can be enhanced by the use of GIS. The first dimension of building capacity in river management concerns the efficient use of personnel and time. There is great potential for automation in GIS, for example in geodata preparation and processing, or in geodata-based administrative processes. Modern GIS offer graphical tools such as the "QGIS Model Designer" or interfaces for Python processing scripts that are executed directly in the GIS software. Of course, this already requires a good basic knowledge of GIS and possibly programming languages.
The use of GIS in river management helps to increase its knowledge base because state-of-the-art GIS can read and process a large variety of data formats. More available data enables more precise, more comprehensive or previously unrealizable evaluations. Especially GIS-based methods for flood risk management (section 3.4.1) can benefit from the integration of remote sensing data (section 3.4.1) and local knowledge via participatory GIS (Canevari-Luzardo et al., 2015).
Additionally, GIS can enhance collaboration in river management (cf. 3.3). Spatial assessments of uses, socio-economic benefits and environmental impacts are highly relevant in "integrated" management concepts (Lorenz et al., 2001). Used as a communication tool (section 3.4.1) GIS help to balance views and interests of different stakeholders (Serra-Llobet et al., 2022). In order to benefit from the potential of GIS applications, digital spatial information on water bodies, associated infrastructure, catchment areas, legal relationships (water rights, owners, etc.) is required. Collaborative river management also emphasizes the need for open data standards, especially when rivers cross administrative borders. The clash of different, subject-specific data standards or the complete lack of data standards can be a significant obstacle to cooperation (Arvidsson et al., 2022). Effective river management requires the collaboration of multiple stakeholders and their ability to work with complex spatial data. GIS training is generally included in technical and university education for water management practitioners. However, many practitioners are still not or not sufficiently familiar

with GIS, as other working routines and tasks are prevailing in their day-to-day business.

Open-source GIS tools have been developed within research projects and published in scientific papers for years. However, the project-related development usually means that researchers only work together with practitioners for a limited period of time (cf. Borowski & Hare, 2006; Zander & Kralisch, 2016). Once pilot schemes have been realized, the knowledge gained must be shared with the relevant stakeholders through training and further education.

Such a training concept was implemented within the framework of the project "OSWeGe" (*Offenes Lernen und Arbeiten mit OpenSource-GIS und Open Data als Werkzeug eines klimaangepassten Gewässermanagements* / Open education and practice for open source GIS and open data as a tool for climate-adapted water management) (OSWeGe, 2024). The OSWeGe project was initiated to support 27 water and soil associations in the federal state of Mecklenburg-Western Pomerania, Germany which are responsible for the management of smaller watercourses. Additionally, the project aimed to establish a standardized approach for the collection and maintenance of river geodata in this region. Standardization is intended to promote a consistent data management and to encourage GIS-supported cooperation between actors of river management of different WBVs.

To tailor the program to participant needs, an initial survey regarding GIS knowledge, the GIS workflows and GIS tools, and related software usage among potential participants supported the concept phase. The survey comprised interviews with GIS experts and questionnaires for the employees of the WBV. The results showed that all WBVs were already using GIS, with QGIS being the most widely used desktop GIS software (see Figure 5.1). Additionally, specific GIS applications for river data management and Web-GIS were in use at the time of the initial survey, whereas mobile GIS applications such as Qfield or LeicaMobile were only sparsely used among the 40 responders. Following the outcomes of the survey, the program focused on open-source GIS tools for digital recording, correction, and analysis of river geodata. Lecturers came from the professorships of water management and geoinformatics

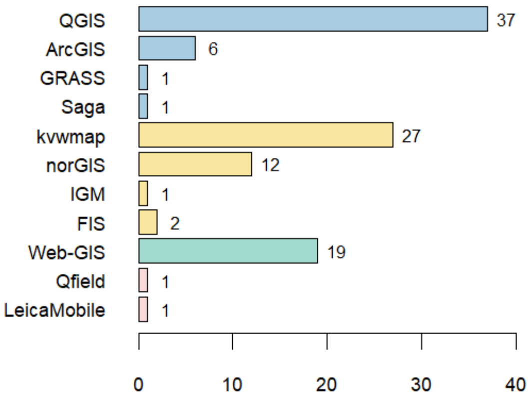


Figure 5.1.: Results from the initial survey (40 responders) on GIS software usage among WBV participants; blue=open-source desktop GIS, yellow=specific, regionally developed GIS applications for river data, green=Web-GIS, red=mobile GIS applications

of the University of Rostock, along with guest speakers from a research institute for moorland restoration and GIS specialists from particular WBVs.

5.1. Workshop program and participants

The OSWeGe project featured a structured workshop program consisting of ten training sessions over the course of one year addressing different GIS-related topics, ranging from basic data acquisition and processing tools to more advanced applications such as flood risk modeling and wetland restoration. Each module was designed to be independent yet progressively more complex, allowing participants to build upon previously acquired knowledge.
The sessions covered:

- Introduction to QGIS basics (Sept 2023) – fundamentals of vector layers, object selection, and querying.

- GIS processing Tools (Nov 2023) – manual editing of vector geometries, raster layers, and georeferencing.
- Digital elevation models (DEM) (Nov 2023) – processing and analysis of terrain models.
- Field survey and QGIS object creation (Jan 2024) – practical field exercise on campus.
- Automating GIS processes (Feb 2024) – spatial and logical linking, CAD data integration.
- DEM analysis (March 2024) – hydrological flow analysis, flood mapping, groundwater estimation.
- Map creation and export (May 2024) – layout design, labeling, and map series generation.
- GIS for climate-adapted river management (Sept 2024) – guest lecture by a regional research organisation on peatland restoration, flood impact assessment.
- FIS-Water and data standardization (Oct 2024) – development of a standardized approach for geodata management.
- Final workshop (Nov 2024) – review, feedback, and selected QGIS exercises.

Throughout the project, all lessons, exercises, and supplementary materials were uploaded to an open-access online learning platform (https://ilias.opengeoedu.de/ilias/goto_opengeoedu_pg_11279_136.html) , allowing participants to review and catch up at their convenience. A total of 54 individuals participated, averaging 19 attendees per session. Besides the GIS specialists from the WBVs, the workshops also included representatives from the regional environmental authority (LUNG) and the parent association of the WBVs on a federal state level.

5.2. Outcomes and evaluation

At the final workshop of the training program, the participants' progress was measured through an evaluation survey. The feedback indicated considerable improvements in their ability to apply GIS methods to daily river management tasks (see Figure 5.2). As the face-to-face

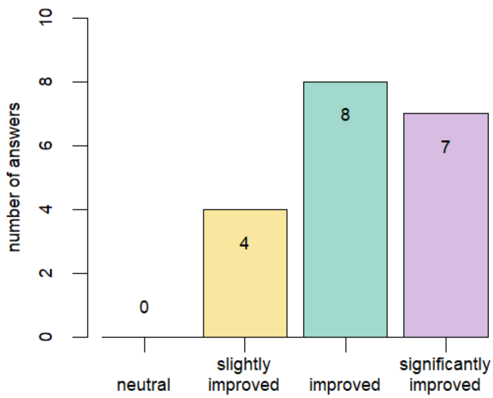


Figure 5.2.: Results from the final evaluation (19 responders), showing participants' self-assessed improvements in GIS proficiency after the training series.

workshops facilitated professional exchanges between GIS specialists and other WBV employees, the OSWeGe project successfully established a user network among river management professionals. Continuous collaboration was also supported through a project mailing list. Additionally, two key outputs emerged from the workshops:

1. **A geodata standardization guide** (Schilling et al., 2025b) developed collaboratively with WBVs and the regional environmental agency (*Landesamt für Umwelt, Naturschutz und Geologie*, LUNG). The guidelines provide best practices for geodata structuring and exchange.

2. **A QGIS plugin for river geodata correction** designed to

help WBVs automate data validation and improve consistency in geodata management. The source code is publicly available on GitHub[1] with a GPL version 3 license.

Such standards have not been previously implemented in M-V for WBVs, making it a pioneering effort in sustainable water management. The project's innovative approach was characterized by the integration of a community-driven development process for standards on river-related geodata and supporting QGIS tools. The results, including all training materials and developed tools, remain accessible via the online learning platform for continued use in education and professional training. With these outcomes, the project has likely initiated a process towards establishing a collaborative, climate-adapted and digital river management in Mecklenburg-Western Pomerania.

1 https://github.com/Jannik-Schilling/OSWeGe_Tools

6. Conclusion of the thesis

Open source software and open data in general provide a variety or benefits – transparency, interoperability, re-usability. These advantages can also be leveraged for the diverse challenges in water management, as they facilitate cooperation between actors across sectors and areas of responsibility. Cooperation and the mutual provision of data is essential for "integrated" water management approaches as described in section 3.3 because of the various interconnections between different fields of action within water management as well as interconnections with other sectors.

Both open data and open source software also reveal potentials for innovation and efficiency. However the examples also indicate several obstacles. In order to draw a more detailed picture, this last chapter critically revises the argument from section 2.2 and outlines possible solutions to overcome the discovered obstacles.

Publishing (spatial) open data as described in the communication chapter contributes to transparency and accountability of governance actors and fosters the participation of stakeholders. The findings from the cited literature (sections 3.3 and 3.4.1 largely support the applicability of the "democratic argument" by Paderta (2012) in the context of water management. The provision of digital maps, geodata and data services (e.g. WMS or WFS) is not only an important part of risk management, but also helps to build trust in public authorities. Meanwhile, public authorities in Germany increasingly provide open geodata in open data portals (cf. section 3.4.2, also because the legal framework conditions are increasingly shifting towards "open by default" (cf. section 2.1.3). A particular feature of the water sector is the diversity of different types and constellations of responsible institutions or operators for the same tasks (cf. section 3.1.3). Accordingly, because not all of the data owners

can be considered part of public administration, it must be noted that the formal argument for open data by Paderta (2012), only applies to a limited extent in water management. In addition, there is a fine line between the public interest in the availability of some of the data in water management and its protection with regard to critical infrastructure (cf. Crochemore et al., 2019).
From a data user perspective, the available open data enables analyses that stakeholders in water management would not be able to perform with their own data. Especially for research purposes, open data can fill data gaps e.g. regarding input data for model-building and urban water management, as shown in section 4.1. Hence, the innovative potential of open data, in particular of open geodata, in water management is significant and has been proofed by numerous publications (for example Crochemore et al., 2019; Mair et al., 2017; Rossetto et al., 2018; Schilling & Tränckner, 2020; Warsta et al., 2017).
However, several challenges may arise here. The first hurdle concerns the licenses in use, as these determine the conditions under which a dataset can be used. Depending on the intended purpose of the data, overly restrictive licenses can be just as problematic as incompatible licenses for different data sets (Happ et al., 2022). This is particularly true of country-specific license types (cf. table 3.4 in section 3.4.2). This in turn means that data providers can encourage innovation by making their data available under internationally established permissive licenses which are compatible to each other (Müller & Weber, 2021).
Additionally, data quality can be an issue. If data has not been collected by the user themselves, they have to trust the data source. The challenge has been discussed widely for user-generated content (UGC) such as OSM (cf. section 4.1). For official open data, this also applies in a modified way. Official data is usually collected for a specific purpose and therefore with a specific level of accuracy that may not correspond to that level of accuracy which is required for subsequent use. Different data collection requirements at different institutions also make it difficult to harmonize data. Metadata that could document measurement accuracy of an open data set, for example, is not always available (Crochemore et al., 2019). The portal for water levels by the LUNG,

for example, explicitly states that the data is untested raw data, some of which comes from automatic measurement systems (LUNG, n.d.-b). The subsequent data quality check by users becomes more and more time-consuming the more different data sources are used, possibly with their own data formats and structures, markers for missing data etc (Crochemore et al., 2019). In the case of spatial data, different coordinate systems and missing information on spatial accuracy may pose a problem (Crochemore et al., 2019). However, many of the challenges listed here could be overcome more and open standardization (cf. section 2.2).

The first and obvious benefit of using open-source software is in terms of financial resources, because it is generally freely available. Since the definition of open source requires the support open file formats (cf. 2019/1024/EU and OKF, 2015)) the risk of follow-up costs by the so-called "lock-in effect" can be avoided. This is often the case with proprietary software, e.g. if the export of data is not possible or (often at additional cost) only possible via other proprietary software from the same manufacturer (OKF-DE, 2020; Paderta, 2012). However, Swain et al. (2015) argues that open source applications often represent isolated solutions with single functionalities. Hence, linking different open source software as shown through the examples of Python-based packages in sections 3.4 can be considered as an enabler for their successful use. Such links in terms of software may also refer to linking different sectors, as needed for the integrated water management approaches described in section 3.3.

As described in section 2.2, public accessibility of the code base enables a sustainable adjustments of the software by the user community according to their needs (Löwe et al., 2022). This also applies to the water sector, which was illustrated with the examples of modeling and GIS (cf. sections 3.4.2 and 4). The argument of adaptability seems particularly relevant in view of climate changes (section 3.2.3) with uncertain probabilities of occurrence, which may require a rapid response time. In this context, independence from proprietary providers is an important factor for the resilience of water management actors, enabling them to act quickly to changing requirements in the event of a crisis (cf. OKF-

DE, 2020).

Gathering expertise in free and open source software might also make stakeholders become future facilitators, encouraging others to participate in using the available open source tools, open data and open standards. Sharing code and river-related data with open licenses enables third party developers or scientists to research, develop standards among institutions and make the results publicly available again (cf. Zander & Kralisch, 2016). One prominent example is the modeling tool SWMM (section 3.4.2) with its numerous derived software packages and further developments. Hence, the "innovation argument" clearly applies for open source software. However, not only the development but also the maintenance of open source applications needs support by public funding (OKF-DE, 2020).

The overall picture that emerges is one in which open data and open source contribute significantly to the "capacity" of the stakeholders in water management. The potentials could be illustrated by the examples of GIS and modeling software in combination with open spatial data. The evaluation of the project OSWeGe in conjunction with the practical experience from the GIS workshops indicate that the application examples adapted to the needs of the participants as well as the guidelines on the standardization of geodata in particular support capacity building.

To make capacity building effective at an institutional level, open source training programs (e.g. for GIS) as described in section 5.1 must take place in the long term, mainly because climate-related and societal requirements for water management will constantly change (cf. OKF-DE, 2020). In parallel, the ongoing digitalization requires the development of continuing education concepts for specialists and an adjustment of existing training standards (DWA, 2020a). Open educational resources, e.g. as provided by the OSWeGe project, should therefore be specifically promoted, to unlock the potential and – as the subtitle of the NGIS 2.0. advises to do – "simply use geoinformation" ("*Geoinformation einfach nutzen*") (Weke et al., 2024a).

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Appendices

A. Tables

Table A.1.: Usage of SWMM, e.g. as part of other software

Type	Software or package name	Purpose / SWMM usage	Open	Since	Reference
SWMM Source Code	EPA-SWMM	Original Stormwater Management Model developed by the US EPA	Yes	1971[1]	Rossman et al. (2004)
	OWA-SWMM	Open source / community version	Yes	2016	McDonnell et al. (2021)
GUIS	XPSWMM	One of the first graphical user interfaces	No	1988	Shamsi (1997)
	WSWMM	Integration in CAD	-	1994	Shamsi (1997)
	ICM SWMM	Integration in Autodesk Infoworks	No	2019	Autodesk Inc. (2024)
	Autodesk Storm and Sanitary Analysis	Extension for Autodesk Civil 3D	No	-	Autodesk Inc. (2021)
	Flood Modeller	Integration as solver (among others)	No	-	Jacobs (n.d.)
	Fluidit Sewer	Software to optimize sewer systems	No	-	Fluidit Ldt. (n.d.) and Sunela et al. (2024)
	InfoDrainage	Design software for stormwater and sanitary sewer networks	No	-	Innovyze (2022)
	SewerGEMS, CivilStorm	Integration with the Bentley Systems OpenFlows product group	No	-	Bentley Systems Inc. (2024)
	Tuflow	SWMM as an alternative to the ESTRY (1D) Solver	No [2]	-	Tuflow (2023)
	VO SWMM	SWMM GUI with built-in GIS tools	No	-	Smart City Water Inc. (n.d.)
GIS-Integration	PCSWMM	Spatial decision support system for SWMM	No	1984	CHI (n.d.) and Shamsi (1997, 1998)
	SWMENU	developed for automated generation and execution of models	-	1991	Shamsi (1997)

[1] first developement since 1969
[2] but Open Source-QGIS-Plugin, see Tuflow (n.d.)

Table A.1.: Usage of SWMM, e.g. as part of other software (continued)

Type	Software or package name	Purpose / SWMM usage	Open	Since	Reference
	SWMMDUET	Integration in ESRI Arcview	-	1993	Curtis (1994)
	AVSAND	Integration in ESRI Arcview	No	1997	Shamsi (1998)
	MIKE+	Integration with ESRI ArcGIS; Since 1997: Mike SWMM; later on: name change to MIKE URBAN and to MIKE+	No	1997	Kjelds (1997)
	SWMMTools	Integration in ESRI Arcview	Yes	2000	Heineman (2001)
	AGSWMM	Integration in Arcview	No	2005	Shamsi (1998)
	InfoSWMM	SWMM modelling software built with ESRI ArcGIS	No	2005	Boulos et al. (2006) and Innovyze (n.d.)
	qgis-swmm	Running SWMM models within QGIS (not maintained any longer)	Yes	2013	Mora (2013)
	Giswater	Open-source tool for the integral water cycle management	Yes	2014	Giswater (n.d.)
	GISpipe	GIS based modelling software (integrates SWMM and EPANET)	No	2015	JinboSoft (2015)
	GisToSWMM5	Setup of SWMM models from raster files	Yes	2017	Warsta et al. (2017)
	QKAN	Management of drainage system data with QGIS	Yes	2017	Höttges (2017)
	generate_swmm_inp	Import and export SWMM models from/to QGIS	Yes	2020	Schilling and Tränckner (2022)
	GeoSWMM	Integration in ESRI ArcGIS Pro	No	-	Streams Tech Inc. (n.d.) and Utilian Inc. (n.d.)
	AquaTwin-Sewer	Software extension for ESRI ArcGIS Pro	No	-	Aquanuity (2023)

Table A.1.: Usage of SWMM, e.g. as part of other software (continued)

Type	Software or package name	Purpose / SWMM usage	Open	Since	Reference
Python Library	swmmout	Reading SWMM output (.out) files	Yes	2012	Townshend (2012)
	swmm5-python	SWMM5 Python calling interface	Yes	2013	Pathirana (2024)
	swmmtoolbox	Reading SWMM output (.out) files	Yes	2014	Cera (2025)
	swmm toolkit	Python wrappers for the swmm-solver and swmm-output	Yes	2014	Banik et al. (2014)
	PySWMM	Very active open source project developping a python interface to SWMM functionality	Yes	2016	McDonnell et al. (2020)
	swmmio	modification of SWMM input (.inp) files, visualisation of results	Yes	2016	Erispaha (2022)
	SWMMOutputAPI	Reading SWMM output (.out) files (not maintained any longer)	Yes	2016	McDonnell et al. (2016)
	hymo / swmmreport	Reading SWMM input (.inp) and report (.rpt) files	Yes	2017	Nguyen et al. (2017)
	shmm	Conversion of geodata (shapefiles) into SWMM input (.inp) files	Yes	2018	Nguyen (2018)
	OSTRICH-SWMM	Optimization of green infrastructure with Optimization Software Toolkit	Yes	2019	Macro et al. (2019)
	swmm_api	Automation, Customization, and Visualization of SWMM models	Yes	2019	Pichler (2022)
	swmm-pandas	Interface between several SWMM files and the pandas python package	Yes	2021	Karos (2021)
	swmmtonetcdf	Conversion of SWMM output files (.out) to netcdf	Yes	2022	Buahin (2022)
	SWMManywhere	Creation of a synthetic urban drainage network from open data	Yes	2025	Dobson et al. (2025)

Table A.1.: Usage of SWMM, e.g. as part of other software (continued)

Type	Software or package name	Purpose / SWMM usage	Open	Since	Reference
R package	SWMMr	Read and write SWMM input files (.inp); analysis and visualisation of model results with the R language	Yes	2019	Leutnant et al. (2019)
	kwb.swmm	integrates SWMMr; adds advanced analysis and preparation functions for SWMM models	Yes	2024	Rustler (2024)
Matlab	MatSWMM	analysis and design of real-time control (RTC) strategies in urban drainage systems	Yes	2016	Riaño-Briceño et al. (2016)
TypeScript	swmmNode	interaction with SWMM files via Node.js or SwmmReact (see below)	Yes	2023	Gardner (2023)
others	integration into SIMBA	SWMM as one of several available solvers; Import of SWMM input (.inp) files	-	2013	Alex et al. (2024)
	IberSWMM+, IberSWMM	Coupling Iber with SWMM	No	2020	Sañudo et al. (2025) and Sañudo et al. (2020)
	SWMM5+	Additional solution for the dynamic wave equation (Saint-Venant equations) written in FORTRAN	Yes	2021	Hodges et al. (2021)
	SwmmReact	web interface for EPA-SWMM modeling systems	Yes	-	Swmmreact (n.d.)
	various software solutions	Coupling with 2D models	-	-	Buttinger-Kreuzhuber et al. (2022), Leandro and Martins (2016), and Li et al. (2022)

Table A.2.: Factors, areas and target values used in (Schilling & Tränckner, 2020): NI = Number of inhabitants in the catchment; $NI \cdot f_R$ = NI multiplied with rural factor; A_R = residential building area; A_I = industrial building area; A_C = commercial building area, 1st Q. DW = 1st quartile of dry weather inflow to SPS or WWTP; Mean DW = mean of dry weather inflow to SPS or WWTP; LTA WW = long-term average of wastewater inflow to WWTP (see section 4.1.2, Optimization of Parameters) .

N	**NI**	**$NI \cdot f_R$**	**A_R** (m^2)	**A_I** (m^2)	**A_C** (m^2)	**1st Q. DW** (m^3/d)	**Mean DW** (m^3/d)	**LTA DW** (m^3/d)
1	234844	234372	14365079	1660316	5458696	35947	38964	-
2	101706	101769	6194405	371115	2497618	16034	17764	-
3	47755	47373	3133414	900494	1079482	7501	8080	-
4	52353	52353	3136566	108951	915023	6498	7090	-
5	22470	22470	1296892	142960	426274	4189	4329	-
6	5549	5549	319759	114006	480849	1338	1654	-
7	4629	4568	399937	19677	74456	612	706	-
8	2880	2880	199243	39818	20960	391	439	-
9	3238	3022	294551	33333	12372	n.a	n.a	306
10	535	499	49360	0	33654	n.a	n.a	176
11	720	624	109380	0	0	57	73	-
12	250	200	45851	0	449	28	34	-
13	343	320	27872	5271	8046	26	34	-
14	212	170	40671	179	7974	26	30	-
15	105	77	15540	4201	0	13	15	-
16	148	118	21999	5111	771	n.a	n.a	10
17	162	151	14736	0	0	6	8	-
18	100	93	9054	222	0	4	5	-
19	40	37	3211	0	496	n.a	n.a	3
20	48	42	7113	0	0	4	4	-

Table A.3.: SWMM objects and attributes linked to GIS layers in the QGIS plugin “Generate_SWMM _inp”.

Section in SWMM Input File	File Name in Default Data Set	Layer Geometry	Annotations
SUBCATCHMENTS SUBAREAS INFILTRATION	SWMM_subcatchments.gpkg	Polygon	
Polygons			Automatically derived from subcatchment geometries
CONDUITS LOSSES	SWMM_conduits.gpkg	Line	
PUMPS	SWMM_pumps.gpkg	Line	
WEIRS	SWMM_weirs.gpkg	Line	
OUTLETS	SWMM_outlets.gpkg	Line	
ORIFICES	SWMM_orifices.gpkg		
XSECTIONS	-	-	Automatically derived from CONDUITS, WEIRS and ORIFICES
VERTICES	-	-	Automatically derived from line geometries
JUNCTIONS	SWMM_junctions.gpkg	Point	
STORAGES	SWMM_storages.gpkg	Point	
OUTFALLS	SWMM_outfalls.gpkg	Point	
DIVIDERS	SWMM_dividers.gpkg	Point	
COORDINATES	-	-	Automatically derived from point geometries

Table A.4.: SWMM sections, which are saved in tables by the tool "Generate_SWMM _inp".

Section in SWMM Input File	File Name in Default Data Set	Table Names in Excel File
OPTIONS	gisswmm_options.xlsx	OPTIONS
CURVES	gisswmm_curves.xlsx	Rating
		Storage
		Tidal
		Weir
		Pump1
		Pump2
		Pump3
		Pump4
		Pump5
		Control
		Diversion
		Shape
INFLOWS	gisswmm_inflows.xlsx	Direct
DWF		Dry_Weather
PATTERNS	gisswmm_patterns.xlsx	HOURLY
		MONTHLY
		DAILY
		WEEKEND
POLLUTANTS	gisswmm_quality.xlsx	POLLUTANTS
LANDUSES		LANDUSES
BUILDUP		
WASHOFF		
COVERAGES		COVERAGES
LOADINGS		LOADINGS
TIMESERIES	gisswmm_timeseries.xlsx	-
RAINGAGES		
STREETS	gisswmm_streets.xlsx	STREETS
INLETS		INLETS
INLET_USAGE		INLET_USAGE
TRANSECTS	gisswmm_transects.xlsx	Data
		XSections

B. Publication “Spatial Tools for River Management: Capacity Building through GIS” (Schilling et al., 2025a)

B.1. Introduction

The state of river ecosystems around the world is a serious cause for concern. This is primarily due to anthropogenic influences from water use, artificial structures and land use or land cover changes in catchments (Acreman, 1996; Grabowski et al., 2022; Köhler et al., 2024; Rivaes et al., 2022; Tickner et al., 2017). There are very few rivers in the world that have not been impaired by human influence (Vörösmarty et al., 2010). Human-caused impacts on rivers coincide or overlap with direct and indirect effects of climate change (Palmer et al., 2009). As temperatures rise, shifts in all components of the water cycle can be observed (see section B.2.2 for details). As a result, both extremes, flooding after heavy rainfall events and water scarcity in rivers or even rivers temporarily falling dry, are occurring more frequently, which involves massive damage to aquatic ecosystems and infrastructure (Köhler et al., 2024; Palmer et al., 2008; Zhang et al., 2020).

River management is targeted to reconcile a long-term protection of waterbodies and related ecosystems as well as the maintenance of infrastructures and the interests of various stakeholders in using the rivers' ecosystem services (Chatrabhuj et al., 2024; Tickner et al., 2017). In this context, it must deal with impacts from past events (e.g. drought or flooding), existing structural alterations (e.g. dams, river beds) and be prepared for future changes, where possible. Thus, river management

usually includes both, reactive and proactive measures and strategies (Palmer et al., 2009).
However, river management faces complex challenges. They are complex, because there is usually not a single cause, but a combination of drivers for these challenges which are related to climate change, human activities and development, and "inherent problems" such as geological aspects and the spatial structure of catchments (Heasley et al., 2019; Karki et al., 2020). The diversity and interdependence of such processes and factors requires highly interdisciplinary approaches which makes river management even more challenging (Arvidsson et al., 2022; Tickner et al., 2017; Warmink et al., 2017). For example, Tickner et al. (2017) provide a framework for river management research, policy and planning that integrates assessing impacts and benefits of infrastructure and ecosystem services for different societal groups in different locations. Warmink et al. (2017) develop adaptive strategies for policymakers to overcome the uncertainty of long-term changes in river management. However, such concepts often remain on a conceptual level because of complex socio-biophysical dependencies and institutional barriers (Lorenz et al., 2001; Watson, 2004)
All these complex inter-dependencies and processes are in some way spatially related in the river basin (Colby, 2019; Kourgialas et al., 2024; Torrefranca & Otadoy, 2022; Vrebos et al., 2017). Addressing these spatial aspects is therefore decisive for successful river management. This requires suitable data and tools as well capable stakeholders to use them. Therefore, the aim of this paper is i) to provide a comprehensive overview of challenges in river management with their spatial dimension and ii) to elaborate the central role of geographical information systems (GIS) in addressing these challenges and iii) the derive the need and potential of GIS related capacity building for stakeholders. The text is structured in three parts, each defined by a guiding thesis (in italic letters):

Part 1: (Section B.2) "*Challenges in river management are characterised by functional (inter)dependencies. These dependencies arise from spatial aspects such as the topology of river networks, geomorphology and spatial patterns of anthropogenic activities* *or climate change.*" In this part, interdisciplinary literature of the past twenty-five years is explored, showing ongoing and emerging problems.

Part 2: (Section B.3) "*Existing GIS applications can address these challenges in large parts, making GIS a key tool in planning of river management*". The thesis is supported by a series of application examples and case studies described in scientific literature. This part of the paper is subdivided into three subsections covering flood risk management, monitoring and remote sensing, and the use of GIS and maps as a communication tool.

Part 3: (Section B.4) Effective river management requires not only GIS tools but the collaboration of multiple stakeholders and their ability to work with complex spatial data. GIS training is generally included in technical and university education for water management practitioners. However, many practitioners are still not or not sufficiently familiar with GIS, as other working routines and tasks are prevailing in their day-to-day business. Therefore, we postulate that "*to enable informed decision-making, targeted capacity building is essential. This includes strengthening skills, knowledge, and the implementation of standards for handling spatial information.*" The third part is based on interviews, surveys and practical experience from a current project, in which the authors were involved.

B.2. Challenges in river management

This section presents four key challenges in river management. In this context, (inter-)dependencies between challenges and processes are highlighted. Various approaches can be found in scientific papers on water management or water ecosystems that describe and explain such dependencies. For example, with regard to critical infrastructure, Arvidsson et al. (2022) refer to interdependencies as "a relationship when two infrastructures are dependent on each other, either directly or through feedback-loops". Franklin et al. (2024) distinguish between structural and functional “connectivity” in aquatic ecosystems. Heasley et al. (2019), analysed dependencies between the characteristics of rivers and riparian zones (flow type, sediment size, habitat quality and modification) and network topology. A common feature of the mentioned examples is that functional connections and dependencies are explained by spatial aspects (e.g. topology, flow paths, patterns, proximity) at different scales, which is highlighted by a comprehensive review of scientific literature.

B.2.1. Competing interests of use and protection goals

Rivers and streams are used by humans in a many different ways. As part of man-made infrastructure, they are utilized to transport goods, supply energy, or as a receiving watercourse for wastewater and stormwater. Rivers provide water for domestic, agricultural or industrial use or serve as recreational areas. Such benefits for humans are usually referred to as “ecosystem services” (Karki et al., 2020). Among the variety, different claims or types of ecosystem services can be in competition with each other. This challenge is illustrated by Tickner et al. (2017). Their paper shows how physical infrastructures and governance affect the availability of ecosystem services for different groups in society. For example, conflicts about freshwater resources of rivers have been of great interest worldwide for years. Where and when withdrawals can take place, for what purpose and in what quantity, must be coordinated by river management as part of a general water governance (Engle & Lemos, 2010).

Conflicts in which the use of one river ecosystem service precludes another use contain an obvious spatial component. Due to the hierarchical nature of river networks, there is a clear differentiation between what is upstream and downstream of a given point in a river (Heasley et al., 2019; Thoms et al., 2018). The dependency results from the flow path of the water. For example, the extraction of water or the building of dams has an influence on the possibilities for water extraction in downstream river reaches (Palmer et al., 2009).

The use of rivers and streams by humans is also one of the most important stressors for their ecosystems (Lorenz et al., 2001). Man-made structures in rivers' cross sections and embankments have serious impacts on lateral and longitudinal connectivity, and water level and flow. For instance, dykes along rivers are an important element of flood protection for adjacent areas, but at the same time they interrupt lateral connections between ecosystems. Dams built for water retention or hydropower generation in river valleys significantly alter the flow regime and disrupt longitudinal reachability for fish and other migratory species (Franklin et al., 2024; Grabowski et al., 2022). Modified flow regimes downstream of hydropower plants also affect macrophytes, macroalgae, diatoms and macroinvertebrates (Rivaes et al., 2022). Further impacts of physical barriers, abstractions and discharges have been reported in terms of hydromorphology and natural sediment transport (Palmer et al., 2009).

A major challenge in terms of water quality is eutrophication caused by anthropogenic inputs of nutrients. In natural rivers, adjacent riparian areas and floodplains along can act as sinks, whereas in other sections pollutants are transported along the flow path. These functional dependencies of different areas within a catchment (e.g. material exchange processes) are often only recognised by their cartographic representation. A spatial assessment of emission points and flow paths on a watershed scale is therefore crucial to identify sources and endangered ecosystems downstream (Köhler et al., 2024; Kourgialas et al., 2024).

B.2.2. Climate-related challenges

Man-made climate change is measurable worldwide in the form of rising temperatures and this trend is likely to continue in the future. Depending on current and future emission scenarios, the average air temperature is projected to increase by 1.5 - 4 °C until the end of the 21st century The consequences of climate change are visible in the processes of the water cycle and their dynamics. Warmer air temperatures primarily lead temporary drought and to increased evaporation which promotes the occurrence of heavy rainfall due to a higher atmospheric water availability (IPCC, 2023).

Consequently changes can be observed in flow regimes of rivers, water temperatures and average water availability, with significant effects on aquatic ecosystems (Tonkin et al., 2019). They physically influence the structure of habitats, the transport of sediment (Nones, 2020) and organic matter, as well as biodiversity (Rivaes et al., 2022). Increased water temperatures change conditions for biochemical processes, e.g. the pH value or the solubility of substances, and promote algae growth (Köhler et al., 2024).
From an anthropocentric perspective, there are two types of climate-related challenges. Firstly, climate change exacerbates the use-related problems in rivers mentioned in section B.2.1 or creates conflicts of use in the first place. This challenge mainly arises from negative impacts on river ecosystem services. For example, with rising temperatures, there is a an increasing demand for water which intensifies the competition for water resources mentioned above. Additionally, water withdrawals from rivers must be limited to ensure minimum water levels or flows downstream for ecological reasons (Tonkin et al., 2019). Adapting river management to climate change must consider these functional and spatial interdependencies between infrastructure and ecosystems at the watershed scale (Palmer et al., 2009).
Secondly, as a result of climate change, watercourses themselves increasingly pose risks, for example due to flooding (Fernandez et al., 2015; Rahman & Di, 2017). In common definitions, "risk" refers to the combination of the factors hazard, exposure and vulnerability, which is also referred to as the "risk triangle" in various publications (e.g. O'Neill et al., 2016; Ziegelaar & Kuleshov, 2022). Risk assessment is increasingly associated with uncertainties in the context of long-term changing climatic conditions (Warmink et al., 2017). A spatial approach for assessment of flood hazards can help to cope with these uncertainties, because the hydrologic response to precipitation inputs depends on the spatial arrangement of soil properties, river channels and confluences. Spatial metrics of river network structures have been described, for example, by Heasley et al. (2019), including drainage density, stream orders and elevation properties. Examples of corresponding GIS analyses can be found in section B.3.2 of this paper. Incorporating such spatial

assessments into risk reduction programmes requires the availability of detailed and up-to-date data (Canevari-Luzardo et al., 2015).

B.2.3. Challenges caused by land use and land cover change

The ongoing conversion of natural landscapes for agriculture and settlement areas can be observed worldwide. As a change in land use generally also causes a change in land cover, i.e. the physical and biological nature of the land surface (change in vegetation, sealing through development, soil compaction), land use and land cover (LULC) changes are usually regarded as a single phenomenon. Such interventions are noticeable in all components of the water balance (Grabowski et al., 2022). Land use changes within a catchment are also closely related to a variety of water quality parameters (Vrebos et al., 2017). Conversion of forest land to agricultural land and sealing of soils by settlements or traffic areas are particularly relevant. Compared to forest areas, agricultural land tends to be characterized by reduced evaporation, lower water retention through interception and infiltration (Leta et al., 2021). The sealing of surfaces reduces groundwater recharge and increases total and peak run-off after precipitation events and higher soil erosion (Panagos et al., 2015). In rivers, these long-term changes become noticeable as gradual changes of the flow regime and water quality. Changes in land use therefore have a significant impact on flood risk. (Guse et al., 2015) The mentioned effects of land uses changes on river processes can be observed regardless of proximity to the river (Grabowski et al., 2022). Altered flows in rivers also affect the geomorphology, adjacent vegetation and the availability of ecosystem services on various spatial scales. In order to describe the interactions between rivers and adjacent areas Grabowski et al. (2022) introduce the term “land-river interface”. The core of the concept is the delineation of four zones (hydraulic active zone, geomorphic active zone, surface water connected zone, and soil moisture zone), each of which is characterised by specific processes.

To incorporate these interactions in river management, detailed geodata on LULC changes are essetial. For Europe, for example, geodata on land use is available from the CORINE project of the EU Commission's Copernicus Land Monitoring Service (CLMS), providing a harmonized data set with 44 land use classes. The dataset has so far been published for the reference years 1990, 2000, 2006, 2012 and 2018 (CLMS, 2021a). Comparable geodata are available for the USA under the name "National Land Cover" (Homer et al., 2020). Worldwide coverage is provided by the CLMS dataset "Global Dynamic Land Cover" (Buchhorn et al., 2021).

B.2.4. Overlapping responsibilities and river / water management as a cross-sectional task

The tasks and challenges which are illustrated in the sectionsB.2.1 to B.2.3 can never be considered separately from one another. They overlap in the time and affected locations along rivers within catchments and make river management a cross-sectional tasks across different technical disciplines. However, there are usually separate administrative competences for "blue" and "green" and "grey" infrastructure, population, environmental protection, each with their own interests and perspectives (Fliervoet et al., 2015). In addition, there are spatially separate responsibilities, e.g. for watercourses which extend across national borders, federal states, or municipalities (Arvidsson et al., 2022; Lorenz et al., 2001).
Cooperation and collaboration are essential in order to overcome the challenges outlined above (Palmer et al., 2009). Therefore, holistic concepts which include both, nature protection and planning or operation of water-related infrastructure have been developed and discussed in various publications with terms like "Integrated Water Resource Management" (IWRM) or "Integrated River Basin Management" (IRBM) (Tickner et al., 2017). These approaches require a high degree of multidisciplinarity and communication between stakeholders, and thus the mutual provision of (spatial) information (Lorenz et al., 2001). In order to initiate dialogues among stakeholders, the cartographic representation and spatial topological analysis of protected areas, habitats of endangered species, land use as area information or discharge points can be a good starting point. Examples for the use of of maps and GIS as

a communication tool can be found in section B.3.4.

B.3. GIS as a central tool in river management

The challenges presented above demonstrate that river management must address spatial aspects and links (overlaps, topological dependencies). It can be therefore reasonably be concluded that geographical information systems (GIS) and geodata are key tools for stakeholders engaged in river management. GIS are digital tools for processing, merging, analysing and visualizing structured, digital data with a spatial reference ("geodata"). Historically, the term "GIS" comprises hardware, software and associated data or database systems, but it is now often used synonymously for GIS software. This section begins with the general history of GIS followed by three application examples for GIS in river management.

B.3.1. Historic development and current status

The pioneering era of GIS began in the 1960s and evolved with advances in the field of computer science in the 1970s and 1980s. In 1982, Esri released ARC/INFO, the first version of the ArcGIS product line, which is still the market leader in commercial geographic information software today (Waters, 2018). In the same year, the United States Army Corps of Engineers began developing GRASS GIS, which was initially released as public domain software and later as open source (Neteler et al., 2012). In the 1990s, geographic information science increasingly became a scientific discipline. Starting in the 2000s, various open-source GIS (QGIS, SAGA) and software libraries such as GDAL/OGR and PROJ have been developed (Conrad et al., 2015; Löwe et al., 2022).
Open source applications have become well-established alternatives to commercial GIS in recent decades (Conrad et al., 2015; Tebano et al., 2016). Although gaps in documentation and fewer professional support by companies have been reported as potential drawbacks, there is a trend towards open source in public administration and universities (Coetzee et al., 2020). QGIS in particular enjoys great popularity due

to the free availability of software and compatibility with numerous data formats and databases (QGIS project, 2024). Additional functionality can be integrated so-called“plugins”. These tools are created by the user community and distributed with publicly accessible repositories, making the software highly customisable compared to proprietary GIS (Löwe et al., 2022; Schilling & Tränckner, 2022).
In many respects, GIS techniques, river management and modelling have evolved in parallel (Colby, 2019). State-of-the-art GIS technology as well latest developments of GIS tools by research projects have a great potential for stakeholders in river management to enhance their options and efficiency (cf. Chatrabhuj et al., 2024).

B.3.2. Identification of flood risks

The spatial assessment of flood risk is based on “mappable” conditions in GIS that influence hazard, exposure and vulnerability (Figure B.1). Due to the large number of factors, these are often summarized as indicators (Ziegelaar & Kuleshov, 2022). A typical example is the characterization of run-off properties subsequent to a precipitation event, the “hydrological response”, based on the morphology of the water body and catchment area (e.g. in Diakakis, 2010; Singh et al., 2023; Torrefranca & Otadoy, 2022). For example, the paper of Torrefranca and Otadoy (2022) presents a morphometric analysis on the Philippine Bohol Island. In their study, watershed delineation and extraction of the drainage network was performed by applying the qswat plugin of QGIS on a DEM of 5 m × 5 m cell size. Diakakis (2010) used a set of GIS tools from the ArcHydro toolbox for flood hazard mapping in Greece. Their approach was based on an analysis of flow direction, flow accumulation and subcatchment delineation with a DEM with a spatial resolution of 3 m. Using Manning roughness coefficient values estimated by means of Land use data from CORINE land cover they created a flow velocity grid which was used to derive hydrographs and peak discharges of the delineated subcatchments in the subsequent steps of the method. In the final step, the catchment areas were assigned to five hazard classes based on the peak discharges.

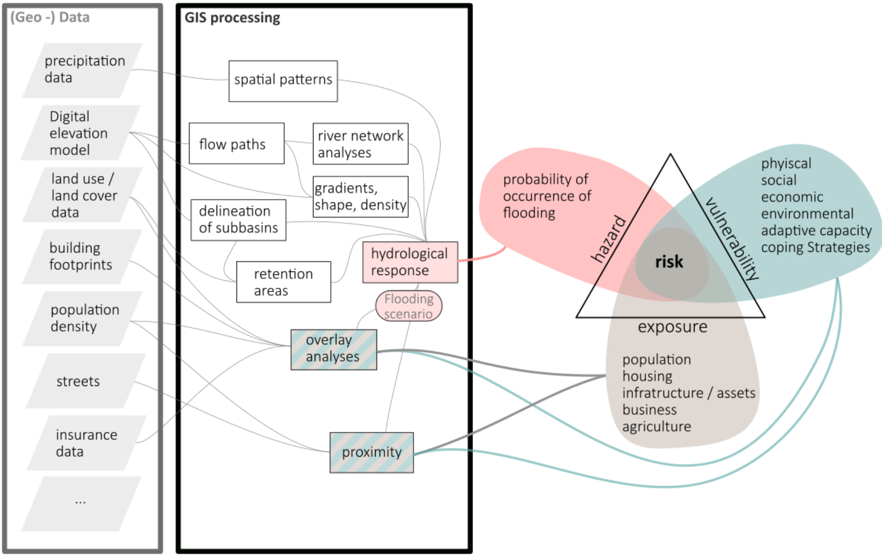

Figure B.1.: Exemplary GIS processing sequence for flood risk assessment as performed in a workshop of the OSWeGe project (section B.4.2). A selection of possible input data is presented on the left side of the illustration. A flooding scenario is developed on the basis of spatial analyses of precipitation, flow paths and catchment parameters. Overlay (intersection) or proximity analyses with land use and population data enable an assessment of exposure and vulnerability. The illustration of risk triangle (cf. section B.2.2) was adapted from de Brito et al. (2017)

GIS can also be used to measure aspects of vulnerability, such as spatially referenced information on financial resources, public and individual protection facilities, age structure and risk awareness (Fernandez et al., 2015). For example, O'Neill et al. (2016) used questionnaires and so-called "cognitive maps" to investigate how residents of the town of Bray on the River Dargle in Ireland perceived their own vulnerability. Their study used a distance analysis to identify proximity to the watercourse and proximity to areas previously affected by flooding as the decisive factors for flooding awareness. A common approach to estimating exposure using GIS is to perform an overlay analysis, as flooding is a spatially clearly delimited event (Arvidsson et al., 2022). Evaluated metrics include the number of buildings, population density or number, location of major transportation routes or infrastructure, and percentage of affected land use classes within an affected area (Ziegelaar & Kuleshov, 2022). Arvidsson et al. (2022) propose spatial analysis and network analysis in GIS to provide information on cascading effects. In particular, critical infrastructures such as power grids, drinking water networks or sewerage systems are spatially assessed in their method, as they often extend over large supply areas, so that a failure at one point has consequences for other areas far beyond those directly affected by the flooding. Combining GIS and machine learning techniques can enhance spatial analyses of large datasets and patterns for flood risk assessment (Tran et al., 2024). For example, the study of Agarwal et al. (2023) investigated extreme annual rainfall patterns across six northeastern Indian states with spatial interpolation (Kriging) and methods such as multiple linear regression, generalized additive models, and random forest.

B.3.3. Monitoring with mobile GIS and remote sensing data

The keyword "monitoring" generally refers to measures and techniques that record and, if necessary, evaluate temporal and / or spatial changes to (sub)systems. Monitoring is applied, e.g. for land use changes, deforestation, erosion and morphology, or the general condition of aquatic and terrestrial ecosystems using indicators (Chatrabhuj et al., 2024).

Another important field of application is monitoring the distribution and abundance of aquatic and semi-aquatic species. GIS-based mapping can be used to track migration movements, changes in species diversity, as well as changes in their habitat conditions. Increasingly, traditional monitoring through field measurements and mapping is being supplemented or replaced by combined digital methods that integrate mobile GIS applications and remote sensing data into the monitoring process (Chatrabhuj et al., 2024). Mobile GIS applications such as QField, ArcGIS Field Maps and Mapit Spatial, which can be installed on smartphones or tablets, are applied to record geometries (points, lines, polygons) and associated attributes in the field. Either the device's internal GPS or an external GPS receiver can be used to get the current position of the mapper. In most cases, cloud-based services provide data transfer to desktop or web GIS software (Nowak et al., 2020). Mobile GIS is used, for example, for mapping endangered or invasive species (Nowak et al., 2020), or to involve citizens in the mapping of water-related objects and floods (Canevari-Luzardo et al., 2015; Fazeli et al., 2015).
Remote sensing methods are used to monitor river morphology in order to identify processes such as erosion and sedimentation in river systems (Colby, 2019; Nones, 2020). This information is crucial for the long-term management of watercourses, as it provides information on how the structure of the watercourse is changing due to natural and anthropogenic influences. The evaluation of satellite images during flood events effectively supports emergency services and decision-makers in assessing potential risks, developing emergency response plans and taking appropriate precautionary measures (Chatrabhuj et al., 2024; Rahman & Di, 2017).

B.3.4. GIS as a communication tool

Analogue and digital maps contain a high density of information, as they combine factual information and spatial context. They show where something is located, which objects are nearby, and which flow paths or water bodies serve as a connection between areas and objects. This combination makes maps the ideal medium for presenting complex issues in river management. Examples are

- **maps in third party communication**, to inform the companies carrying out the field work and highlight possible obstacles or access routes.
- **flood hazard maps and flood risk maps** as proposed by the European Flood Risk Management Directive (Arvidsson et al., 2022), to enhance collaboration of local authorities, associations and residents
- **maps in participation processes** to increase the acceptance of projects and measures and serve as interactive tools for citizens (Chatrabhuj et al., 2024).

Information can be shared as printed printed maps web services with standard protocols developed by the Open Geospacial Consortium, e.g WMS, WMTS or WPS.

B.4. Capacity building by GIS training

Typically, local authorities (offices, associations) bear the responsibility for river management and must employ qualified personnel this for this task. However, at this administrative level it is challenging to establish the required expertise, due to limited financial or temporal resources (Arvidsson et al., 2022). River management tasks have therefore frequently been outsourced to external service providers in the past, a practice which lead to a loss of expertise or “capacity”.
The term “capacity building” refers to the ability of a stakeholder, organisation, authority, etc. to fulfil its functions, solve problems and achieve its goals (Alaerts & Kaspersma, 2022). Capacity building thus includes resources in the form of technical knowledge and skills, time and personnel, infrastructure, tools and goods, as well as networks with others in order to benefit from their capacities. Depending on the addressed challenge, different aspects are emphasized. For example, Engle and Lemos (2010) explore how governance mechanisms contribute to adaptive capacity in river basin management whereas Alaerts and

Kaspersma (2022) highlight learning, knowledge generation and sharing within institutions. We argue that in the context of river management, capacity can be built on various institutional levels if GIS tools are used efficiently to overcome the challenges illustrated in section B.2. In the last section of this article we present potential and requirements of GIS in for capacity building in river management as well as an implementation example from a project in Germany.

B.4.1. Potentials and requirements

There are various dimensions of capacity building which can be enhanced by the use of GIS. The first dimension of building capacity in river management concerns the efficient use of personnel and time. There is great potential for automation in GIS, for example in geodata preparation and processing, or in geodata-based administrative processes. Modern GIS offer graphical tools such as the "QGIS Model Designer" or interfaces for Python processing scripts that are executed directly in the GIS software. Of course, this already requires a good basic knowledge of GIS and possibly programming languages.

The use of GIS in river management helps to increase its knowledge base because state-of-the-art GIS can read and process a large variety of data formats. More available data enables more precise, more comprehensive or previously unrealisable evaluations. Especially GIS-based methods for flood risk management (section B.3.2) can benefit from the integration of remote sensing data (section B.3.3) and local knowledge via participatory GIS (Canevari-Luzardo et al., 2015).

Additionally, GIS can enhance collaboration in river management. Spatial assessments of uses, socio-economic benefits and environmental impacts are highly relevant in "integrated" management concepts (Lorenz et al., 2001). Used as a communication tool (section B.3.4) GIS help to balance views and interests of different stakeholders (Serra-Llobet et al., 2022). In order to benefit from the potential of GIS applications, digital spatial information on water bodies, associated infrastructure, catchment areas, legal relationships (water rights, owners, etc.) is required. Collaborative river management also emphasises the need for data stan-

dards, especially when rivers cross administrative borders. The clash of different, subject-specific data standards or the complete lack of data standards can be a significant obstacle to cooperation (Arvidsson et al., 2022).
There is great potential for building capacity in the use of open-source GIS software, not only because it is free to use. Making the code base accessible to the public enables a sustainable development and adjustment of the software by a user community according to their needs (Löwe et al., 2022). Additionally, the use of open-source software is also beneficial in terms of financial resources, because proprietary software entails the risk of a "lock-in effect", e.g. if the export of data is not possible or (often at additional cost) only possible via other proprietary software from the same manufacturer.

B.4.2. Implementation example

The project "OSWeGe" (*Offenes Lernen und Arbeiten mit OpenSource-GIS und Open Data als Werkzeug eines klimaangepassten Gewässermanagements* / Open education and practice for open source GIS and open data as a tool for climate-adapted water management) was initiated to support 27 water and soil associations (*Wasser- und Bodenverbände*, WBV) in the federal state of Mecklenburg-West Pomerania, Germany (OSWeGe, 2024). These associations are responsible for the management of smaller watercourses. Additionally, the project aimed to establish a standardized approach for the collection and maintenance of river geodata in this region to promote cooperation between actors of river management of different WBVs.
An initial survey regarding GIS knowledge, the GIS workflows and GIS tools, and related software usage among potential participants supported the concept phase. The survey comprised interviews with GIS experts and questionnaires for the employees of the WBV. The results showed that all WBVs were already using GIS, with QGIS being the most widely used desktop GIS software (see Figure B.2). Additionally, specific GIS applications for river data management and Web-GIS were in use at the time of the initial survey, whereas mobile GIS applications

such as Qfield or LeicaMobile were only sparsely used among the 40 responders. Following the outcomes of the survey, the program focussed

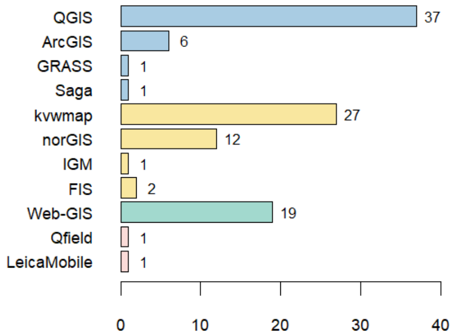

Figure B.2.: Results from the initial survey (40 responders) on GIS software usage among WBV participants; blue=open-source desktop GIS, yellow=specific, regionally developed GIS applications for river data, green=Web-GIS, red=mobile GIS applications

on open-source GIS tools for digital recording, correction, and analysis of river geodata. Lecturers came from the professorships of water management and geoinformatics of the University of Rostock, along with guest speakers from a research institute for peatland restoration and GIS specialists from particular WBVs.

Workshop program and participants

The OSWeGe project featured a structured workshop program consisting of ten training sessions over the course of one year addressing different GIS-related topics, ranging from basic data acquisition and processing tools to more advanced applications such as flood risk modelling and wetland restoration. Each module was designed to be independent yet progressively more complex, allowing participants to build upon previously acquired knowledge.

The sessions covered:

- an introduction to QGIS basics (vector layers, object selection)
- manual editing of vector geometries, raster layers, and georeferencing,
- processing and analysis of DEM,
- practical field survey exercises,
- spatial joins, automating GIS processes,
- hydrological flow analysis, flood mapping, groundwater estimation
- map creation and export,
- a guest lecture by a regional research organisation on peatland restoration,
- data standardization and
- repetition of selected QGIS exercises.

Outcomes and evaluation

A total of 54 individuals participated, averaging 19 attendees per session. Besides the GIS specialists from the WBVs, the workshops also included representatives from the regional environmental authority. The participants' progress was measured through an evaluation survey. The feedback indicated considerable improvements in their ability to apply GIS methods to daily river management tasks (see Figure B.3). As the face-to-face workshops facilitated professional exchanges between GIS specialists and other WBV employees, the OSWeGe project successfully established a user network among river management professionals. Continuous collaboration was also supported through a project mailing list. Additionally, two key outputs emerged from the workshops:

1. **A geodata standardization guide** developed collaboratively with WBVs and the regional environmental agency. The guidelines provide best practices for geodata structuring and exchange.
2. **A QGIS plugin for river geodata correction** designed to help WBVs automate data validation and improve consistency

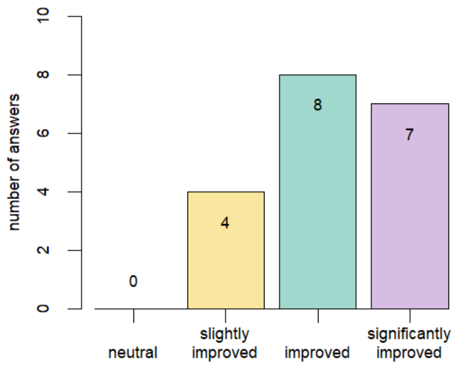

Figure B.3.: Results from the final evaluation (19 responders), showing participants' self-assessed improvements in GIS proficiency after the training series.

in geodata management. The source code is publicly available on GitHub (https://github.com/Jannik-Schilling/OSWeGe_Tools) with a GPL version 3 license.

Such standards have not been previously implemented, making it a pioneering effort in sustainable water management. The project's innovative approach is characterised by the integration of a community-driven development process for standards and supporting QGIS tools. The results, including all training materials and developed tools, remain accessible via the online learning platform for continued use in education and professional training. With these outcomes, the project has likely initiated a process towards establishing a collaborative, climate-adapted and digital river management in Mecklenburg-West Pomerania.

B.5. Conclusions and recommendations

River management is facing diverse challenges. As shown in section B.2, many of these challenges are spatially dependent, mainly due to the hierarchical structure of subcatchments and river networks (upstream to downstream). As the challenges are not solely attributable to spatial aspects, but also to issues of responsibility and governance (Engle & Lemos, 2010; Tickner et al., 2017), thesis 1 can only be partially confirmed. Nonetheless, the application examples and case studies cited in section B.3 demonstrate that GIS is a pivotal instrument in river management (thesis 2). This is due to the fact that GIS facilitate not only spatial analysis and data processing, but also encourage collaboration and cooperation, which are essential to address the challenges outlined above. The evaluation of the project in conjunction with the practical experience from the GIS workshops supports the third thesis. The findings from the individual interviews indicate that the application examples adapted to the needs of the participants as well as the guidelines on the standardization of geodata in particular support capacity building.

To make capacity building effective at an institutional level, the GIS training programmes described in section B.4 must take place in the long term, mainly because climate-related and societal requirements for river management will constantly change. Likewise, uncertainties of the funding policy framework and funding objectives for river protection will remain challenging. The latter is also an important argument in favour of the use, development and enhancement of open-source software, as well as the use and promotion of open data by the institutions which are responsible for river management. Gathering expertise in free and open source GIS is not only essential to become independent of short-term budget planning and to customise software according to one's own needs. The strategy might also make stakeholders become future facilitators, encouraging others to participate in GIS-driven river management with the available tools, data and standards. Sharing code and river-related data with "open" licenses enables third party developers or scientists to research, develop standards among institutions and make the results publicly available again (cf. Zander & Kralisch, 2016).

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