Schriftenreihe Umweltingenieurwesen

Band 103

Dissertation

Muhammad Waseem

Integrated Hydrological and Mass Balance Assessment in a German Lowland Catchment with a Coupled Hydrologic and Hydraulic Modelling

Professur

Wasserwirtschaft

Agrar- und Umweltwissenschaftliche Fakultät

Universität Rostock

Traditio et Innovatio

Dissertation

HERAUSGEBER

Prof. Dr.-Ing. habil. Jens Tränckner
Universität Rostock
Agrar- und Umweltwissenschaftliche Fakultät
Professur Wasserwirtschaft
18051 Rostock

CIP-KURZTITELAUFNAHME

Dissertation Muhammad Waseem
Universität Rostock
Agrar- und Umweltwissenschaftliche Fakultät
Rostock, 2021

© Universität Rostock, Agrar- und Umweltwissenschaftliche Fakultät,
18051 Rostock

BEZUGSMÖGLICHKEITEN

Universität Rostock
Universitätsbibliothek, Schriftentausch,
18051 Rostock
Tel.: 0381/498-8637, Fax: 0381/498-8632
E-Mail: maria.schumacher@ub.uni-rostock.de

Universität Rostock
Agrar- und Umweltwissenschaftliche Fakultät
Professur Wasserwirtschaft
Satower Straße 48, 18059 Rostock
Tel.: 0381/498-3461, Fax: 0381/498-3462

ISBN 978-3-86009-521-8
DOI: https://doi.org/10.18453/rosdok_id00002884

Universität Rostock
Professur Wasserwirtschaft

Vorwort

Zur Erreichung der Ziele der europäischen Wasserrahmenrichtlinien sind zwingend weitergehende Anstrengungen zur Verbesserung der physikalisch-chemischen Wasserbeschaffenheit erforderlich. Im Bundesland Mecklenburg-Vorpommern (MV), betrifft dies insbesondere die Reduzierung der Nährstoffparameter Stickstoff und Phosphor. Die Entwicklung reduktionswirksamer Maßnahmen benötigt eine gute Kenntnis der Eintragspfade und Transport-/Transformationsprozesse. Grundvoraussetzung hierfür ist ein belastbares Monitoring. Das Bundesland Mecklenburg-Vorpommern betreibt gegenwärtig ca. 240 quantitative Messstellen für Oberflächengewässer und 610 Grundwasserpegel. Dem stehen knapp 50 Gewässergütemessstellen für Oberflächengewässer und 133 Grundwassermessstellen gegenüber[1]. Letztere werden nur stichprobenartig (in der Regel monatlich) untersucht. Trotz des damit verbundenen erheblichen personellen und finanziellen Aufwands ist die räumliche und zeitliche Auflösung des behördlichen Monitorings kaum ausreichend, um räumlich ausreichend differenzierte Aussagen zu Eintragspfaden und damit zu erforderlichen Reduktionsmaßnahmen abzuleiten. Dies gilt insbesondere in Bezug auf diffuse Nährstoffeinträge, welche sich im Gegensatz zu Kläranlagen nicht durch Messungen an einem diskreten Emissionspunkt erfassen lassen. Es ist deshalb notwendig, die integral erfasste Belastungssituation an den Gewässermessstellen durch Modellierung oder intelligente Datenauswertung räumlich und zeitlich besser aufzulösen und im Idealfall quantitativ verschiedenen Eintragspfaden zuzuordnen. Echte Prozessmodelle benötigen hierfür zusätzliche Eingangsdaten, welche nur bedingt verfügbar sind (z.B. schlaggenaue Informationen zur landwirtschaftlichen Aktivität). Umso wichtiger ist es deshalb, die bereits verfügbaren Daten prozessorientiert auszuwerten und miteinander sinnvoll zu kombinieren. Hier setzt die Arbeit von Muhammad Waseem an. Ziel der von ihm entwickelten und untersuchten Ansätze ist die Diskretisierung behördlicher Monitoringdaten in Raum (Teileinzugsgebiete), Zeit (Tag) und wesentlichem Eintragspfad (Grundwasser, Drainage, Punktquelle). Grundidee ist die Kopplung eines verbesserten hydrologischen Verständnisses vom Einzugsgebiet mit den wenigen verfügbaren Gütemessungen. Hierfür nutzt er zwei Ansätze mit unterschiedlicher Komplexität: i) rein datengetrieben, ii) durch Erstellung eines hochaufgelösten hydrologisch-hydrodynamischen Prozessmodells.

Die Ergebnisse zeigen, dass bereits mit etablierten hydrologischen Methoden der Datenauswertung (Ganglinienseparation, Darcy-Ansatz) eine Differenzierung der Eintragspfade (Grundwasser, Drainagen, Oberflächenabfluss, Punktquellen) möglich ist. Ein hochaufgelöstes hydrologisches Modell ermöglicht eine weitergehende

[1] https://www.wrrl-mv.de/static/WRRL/Dateien/Dokumente/Service/Dokumente/2016_MV_messnetz_OGW_GW.pdf

Differenzierung in Teileinzugsgebiete und eine überschlägige Bilanzierung gewässerinterner Umsatzprozesse. Weiterhin lassen sich derartige Ansätze auch für eine Optimierung des Monitorings nutzen. Die Methoden sind auch auf andere Gewässersysteme fallweise anpassbar. Es wäre zu wünschen, dass die hier entwickelten Ideen durch die verantwortlichen Institutionen aufgegriffen und in nutzbare Werkzeuge für den behördlichen Vollzug überführt werden.

Die Arbeit entstand im Rahmen des BMBF-Projekts „Bootmonitoring" (FKZ 033W039). Mein besonderer Dank gilt an dieser Stelle dem Projektträger Jülich und dem Staatlichen Amt für Landwirtschaft und Umwelt Mecklenburgische Seenplatte für die hervorragende Kooperation.

Prof. Dr.-Ing. habil. Jens Tränckner

Universität Rostock

Traditio et Innovatio

Ph.D. Thesis

Integrated Hydrological and Mass Balance Assessment in a German Lowland Catchment with a Coupled Hydrologic and Hydraulic Modelling

Cumulative Dissertation
for obtaining the academic degree
Doctor of Engineering (Dr.-Ing.)

Submitted by: **Muhammad Waseem**
Matriculation Number: 215207146

Supervised by: **Prof. Dr.-Ing. habil. Jens Tränckner**

Agrar- und Umweltwissenschaftlichen Fakultät
Universität Rostock

Reviewers

- Prof. Dr. Jens Tränckner, Universität Rostock, Institut für Wasserwirtschaft
- Prof. Dr. Britta Schmalz, Technische Universität Darmstadt, Institut für Wasserbau und Wasserwirtschaft
- Prof. Dr. Zahid Mahmood Khan, Bahauddin Zakariya University, Department of Agriculture Engineering

Year of submission: 2020

Year of Defense: 2021

Kurze Zusammenfassung

Das Tiefland ist vergleichsweise stärker ökologischen und sozioökonomischen Gefahren ausgesetzt, da es einen Schwerpunkt der landwirtschaftlichen Produktion und damit verbundenen landwirtschaftlichen wirtschaftlichen Aktivitäten darstellt. Im Einzugsgebiet des Augrabens wurde eine Datenanalyse mit einfachen Parametrisierungstechniken (Ganglinienseparation und hydraulische Gradientenmethode) durchgeführt, um den Oberflächenabfluss in Basisabfluss und schnelle Abflusskomponenten zu unterteilen. Basierend auf der Schätzung des Basisabflusses mittels Ganglinienseparation wurden die Nitrateinträge über das Grundwasser während Vegetations- und vegetationsfreier Perioden im Einzugsgebiet des Augraben geschätzt. Eine anschließende Modellvergleichsstudie zielte auf die Auswahl eines geeigneten Modellierungswerkzeugs zur Quantifizierung der Hydrologie und Wasserqualität in Tieflandeinzugsgebieten und erläutert und vergleicht verschiedene weit verbreitete integrierte Wassermodellierungswerkzeuge, deren Verwendungszweck, Parameter und Prozesse, Einschränkungen, Stärken und deren Anwendbarkeit unter bestimmten Randbedingungen. Basierend auf den Ergebnissen des Modellvergleichs wurde ein integriertes gekoppeltes hydrologisches und hydraulisches Modell (MIKE SHE und MIKE 11) aufgebaut, um die meteorologischen Auswirkungen auf die Wasserhaushaltskomponenten und den Austausch von Grundwasser und Oberflächenwasser zu quantifizieren. Durch Kombination hydrologischer Modellergebnisse mit begrenzt verfügbaren Wasserqualitätsdaten wurde die Dynamik von Wasserhaushalt/Abfluss und Wasserqualitätsparametern auf die Ebene von Teileinzugsgebieten projiziert. Die Ergebnisse dieser Studie können von den lokalen Umweltschutzbehörden verwendet werden, um das Einzugsgebietsmanagement zu verbessern und kritische Bereiche zu identifizieren, die erhöhte Anstrengungen zur Erreichung der WRRL-Ziele erfordern. Der in dieser Studie verwendete methodische Rahmen kann auf andere Fließgewässer des norddeutschen Tieflands übertragen werden.

Thesis Summary

Water resources management requires proper assessment and management of the watershed combined with constant monitoring of surface water (SW) and groundwater (GW) quality and quantity. Environmental policy decisions and successful management execution needs robust and meaningful methods for assessing the hydrology and water quality variations in a particular catchment. It further helps in determining the estimated and achieved compliance with the desired watershed management objectives.

Lowlands are comparatively more exposed to environmental and socioeconomic hazards being an epicenter for agricultural production and related agricultural economic activities. Hydrological processes in moderate climate lowland catchments can be complicated. Lowland catchments are characterized by a high GW table, low flow velocity, flat topography, and a significant presence of organic soils. Due to glacial telescoping, morphology and geology is partly highly heterogeneous. Lack of topography increases their susceptibility to flooding, climate change, and deterioration of water quality resulting from low flow velocities and higher GW tables. Due to high GW tables, lowland catchments are usually heavily regulated with the provision of drainage systems that result in eutrophication in rivers and lakes due to the reduction in water and nutrient retention times. Decreased retention times means that the fertilizer applied to the crops/plants does not have sufficient time to be taken up by the plants or to decompose through denitrification, resulting in in GW quality deterioration. GW base flow, and more importantly the drainage flow, increases the nutrient concentrations in SW bodies and causes higher algae growth and low oxygen levels in SWs. Due to complex SW and GW interactions, and due to this complexity, precise hydrological water balance information is a prerequisite to develop management practices for the sustainable use of water resources. Integrated hydrological models play an essential role by providing the necessary information regarding the detailed water balance, and SW and GW interactions within a catchment to develop and improve the management practices of water resources.

In Europe, agricultural activities continue to affect the SW and GW quality in terms of NO_3-N pollution. The EU nitrate directive was introduced in 1991 to identify and reduce the NO_3-N pollution in water bodies (Directive 91/676/EEC), and it focuses on integrated management of water in river catchments to acquire, improve, or maintain a good chemical and ecological status. Despite enormous efforts, a large ratio of European GW and SW bodies still do not comply with the "good chemical and ecological status"

according to the defined criteria of the European water framework directive (EU-WFD). One reason is the still-poor identification, quantification, and management of diffuse pollution sources. The EU-WFD demands to reach a good chemical and ecological status of freshwater bodies by the year 2027. In the case of Germany, improvements are required due to the possible surplus use of agricultural fertilizers. Germany is continuously struggling with GW NO_3-N concentrations higher than 11.3 mg/L, a threshold for a "good chemical and ecological status" of GW. Due to deficiencies in implementing the ordinance of agriculture fertilizer application and surplus use of both synthetic and organic fertilizers, a rise in NO_3-N concentrations in comparison to the reported NO_3-N concentrations from 2004 to 2007 is observed.

In this context, the overall objective of this cumulative thesis is to provide and assess tools for a process oriented analysis of hydrologic and eutrophication processes in lowlands, based on available monitoring data. Tollense River has been taken as a representative of northeastern German lowland catchment. Nutrient levels in Tollense and its tributaries is a concern for achieving good chemical status of Tollense river. Hydrological and water quality modelling is important to understand the dynamics and as well as to identify the critical pollution levels in the water body as the mass balances are not sufficient in order to understand the dynamics and transport patterns of nutrients through surface and subsurface sources. So the Tollense river basin represents all the hydrological, hydraulic and water quality processes in terms of nitrogen diffuse pollution in addition to particular lowland catchment characteristics such as backwater effect, control structures, pump flows, eutrophication, decreased retention times due to provision of drainage, high GW and higher inter and base flows.

The research questions of the present study include:

- Data demand, effort and expressiveness of robust methods and detailed physically based hydrological models for the estimation of hydrology and mass balance in a lowland catchment.
- Suitability of semi-distributed and distributed hydrological models to estimate hydrology and diffuse water pollution in North-Eastern Germany lowland catchments with intensive agricultural land use.
- Simulation of SW and GW hydrology in a lowland catchment with a coupled hydrologic and hydraulic model to quantify the meteorological effects on water

balance components and the exchange of GW and SW during dry and wet hydrological years.

- Developing an approach to conduct a detailed mass balance analysis by using the low frequency monitored data in combination with hydrological modelling.

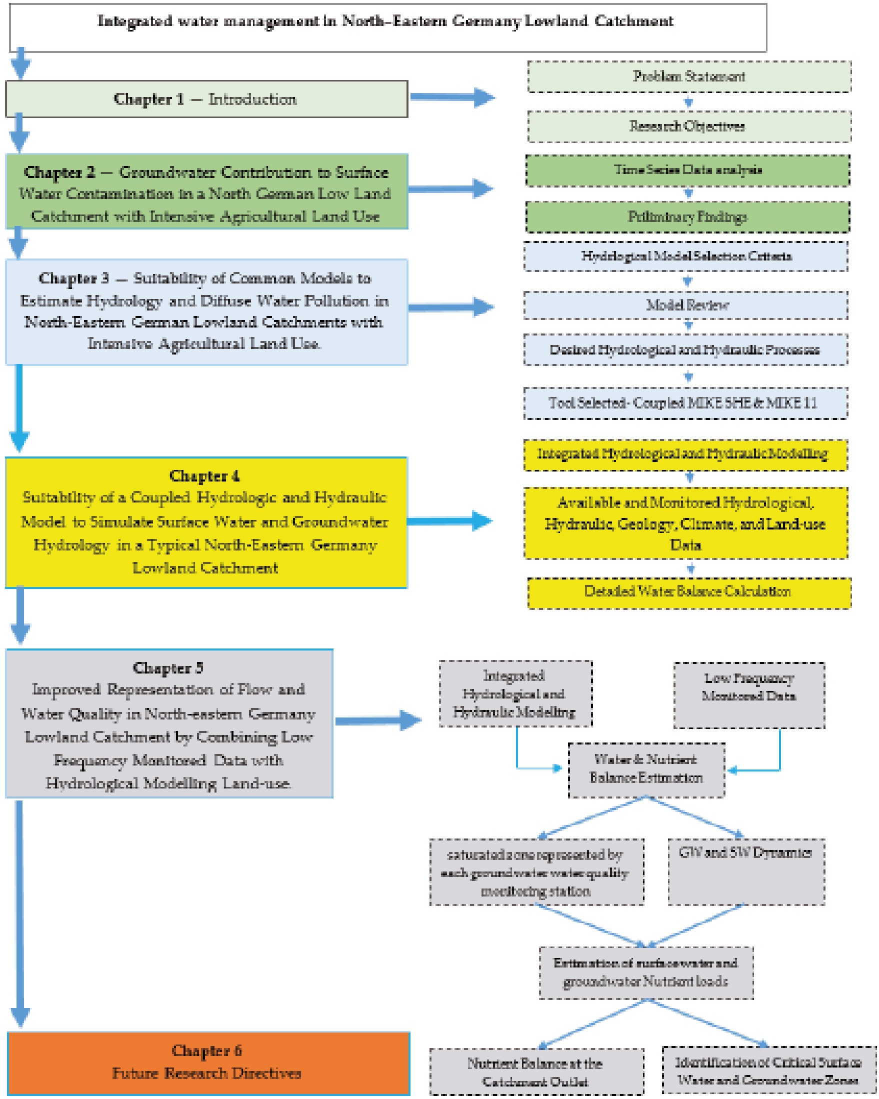


Figure a. Methodological framework used in this study

The current study is carried out in Tollense river basin. Tollense river starts as an outflow of the lake Tollense (at the city Neubrandenburg) Neubrandenburg) and flows about 68 km through a glacier terrain to its confluence with river Peene in the small town Demmin. The presented study was performed on the downstream section of the Tollense river with an approximate length of 30 km, staring from Klempenow to Demmin, with an average catchment area of about 400 km².

In this study the mentioned objectives were achieved on the basis methodological framework explained in **Figure (a)**. Initially the robust analysis of the available time series data was conducted to understand the problem extent and to find important relationships between different parameters. By applying hydrograph separation techniques on observed flow hydrograph the flow was divided into base flow and quick flow. GW levels (contours) in the study area were developed on the basis of average GW tables at available boreholes in the study area. Based on constructed GW contours the catchment was divided into four sub catchments. Simple parametrization techniques were used to quantify the GW and SW flows from sub catchments. The study uses available SW and GW quality data in order to calculate SW and GW NO_3-N loads at sub catchment levels in the Augraben catchment. Further the analysis was done for water quality variations during vegetation and non-vegetation periods. Results of this study effectively provided the estimates of GW and SW interactions, SW and GW dynamics, water quality variations both spatially (in each sub catchment) and temporally (during vegetation and non-vegetation periods). In this time series analysis, applied method provides a robust estimation of GW contribution to NO_3-N loads by using typically available monitoring data of environmental protection authorities. However, a detailed assessment of catchment hydrology requires process based integrated hydrological models.

Secondly, four different process based integrated hydrological models were compared to examine the environmental interactions, transport of solute, flood modelling, and understanding of catchment hydrology. It is always important to select the appropriate hydrological and water quality modelling tools to predict and analyze the lowland catchments and also consider their strengths and weaknesses. Integrated water modelling tools, SWAT (Soil and Water Assessment Tool), SWIM (Soil and Water Integrated Model), HSPF (Hydrological Simulation Program– FORTRAN) and a combination of tools from DHI (MIKE SHE coupled with MIKE 11 and ECO Lab), have been reviewed by focusing mainly on the characteristics of the lowland catchments located in north-eastern Germany. DHI combined tools and SWAT were more suitable for simulating the desired hydrological processes, but in the case of river hydraulics and water quality, the DHI family of tools has an edge due to their integrated coupling between MIKE SHE, MIKE 11 & ECO Lab. In case of SWAT, it needs to be coupled with another tool to model the hydraulics in the Tollense River as SWAT does not include backwater effects and provision of control structures. However, both SWAT and DHI tools are more data demanding in comparison to SWIM and HSPF. For studying nitrogen fate and transport in unsaturated, saturated, and river zone, HSPF was a better model to simulate the desired nitrogen transformation and transport processes. However, for nitrogen dynamics and transformations in shallow streams, ECO Lab had an edge due its flexibility for inclusion of user-desired water quality parameters and processes. In the case of SWIM, most of the input data and governing equations are similar to SWAT but it does not include water bodies (ponds and lakes), wetlands and drainage systems. Coupled MIKE SHE and MIKE 11 model was selected based on this review study to simulate the hydrology in the study area.

After time series analysis and selection of modelling tool, in third phase of this study, a physically-based distributed hydrological model, MIKE SHE, coupled with a hydrodynamic model, MIKE 11, was set-up and calibrated for a typical lowland catchment in moderate climates, the Tollense River in the north-east of Germany. The Tollense river catchment was selected as study area in collaboration with the regional environmental protection agency (StALU-MS) due to its typical characteristics and related typical water management challenges. Large areas are provided with artificial drainage/ GW abstraction pumps to support intensive agriculture in the study area. Tollense river is equipped with two weirs named as Osten and Tückhude to regulate the river flow. The artificial drainage is applied to lower the GW level for agricultural use, especially in the spring months, and accelerates flow and transport of nutrients in the catchment. Depending on the fertilizer application, plant growth state and the meteorological conditions fertilizer applied to the crops is partly washed off in GW and SW, leading to increased nutrient concentrations (namely nitrate) in both systems. Weirs serve opposite to the drainage by raising the SW levels on their upstream side (u/s), and results in SW contribution to the GW. The Tollense river also observes a backwater effect at its confluence with the river Peene in Demmin, due to low hydraulic gradients influenced by the Baltic Sea. In the last decade, the region has faced strongly varying meteorological conditions, with very wet years and partial flooding of agricultural areas (e.g., in 2011 and 2017) and very dry years with partial drought (e.g., in 2018). Due to the close interaction of SW and GW, calibration of GW levels and SW discharges was conducted in parallel. Especially the calibration of GW level became challenging due to the extreme soil heterogeneity, which is typical for glacial soils. Auto calibration was not applied in this study, as the intention was not to enforce an optimum fit between the observed and simulated data, but to gain a better process understanding and to identify the model deficiencies. The calibration process was initiated after the sensitivity analysis and following calibration techniques were applied for the different river flow calibration outcomes. In step 1—when the model was unable to simulate the peak flows, a careful review of the data was done for both the precipitation and river flow, as this happens normally due to the reason that either the rainfall station is not representative or due to the malfunctioning of the precipitation or flow gauges. In step 2—when the model continuously over predicted the flow, evapotranspiration, soil water content, percolation, and GW recharge rates were adjusted. In step 3—where simulated flow followed the observed flow dynamics but lags the actual flow consistently, river bed leakage coefficient rates and Manning's roughness coefficient were adjusted. In step 4—when the model over predicted the peak flows but under predicted the average normal river flows, infiltration rate, interflow, and base flow recession parameters were adjusted. A water balance estimation was performed following the calibration process, as the interest of this study was to get a better insight into the interaction of the different subsystems and hydrological processes in highly GW influenced lowland river basins. The water balance was performed for the whole calibration period and additionally for each hydrologic year, which is defined between 1st October to 30th September of the next year in Germany. The total water input into the model was via precipitation and surface and subsurface inflow, which was further divided into ET, runoff and change in storage, and GW and SW interactions. Water balance error was calculated after balancing all the major hydrological components that includes precipitation, evapotranspiration, runoff, surface and subsurface inflow, and change in storage. With a water balance error of less than 2% during the calibration period, the total estimated water balance is satisfyingly good.

The coupled model resulted in intense interactions among SW and GW. Long term, SW flows follow the pattern of GW levels in the defined catchment with the higher GW flows followed by higher SW discharges. Model calibration of SW discharges was difficult due to the limited monitoring data availability of SW discharges, and that highlights the significance of high resolution field monitoring data in hydrological modelling. GW is a major contributor to the balance of SW flows during the low flow periods, and GW contribution rises up to 45% of total SW flows during the observed partial drought in the catchment; and, with exclusion of river flows from lake Tollense, GW contributes mainly to the Tollense river nearly up to 95% of total SW flows. In the lowland catchment, the unsaturated zone is very shallow during the wet seasons. Due to this, infiltration and evapotranspiration are vital processes that control the rate of recharge. Results illustrate that the saturated zone gains approximately 30%–40% of total precipitation, out of which a major portion is drained to the river via artificial drainage available in the study area. The simulated hydrograph shows relatively overestimated river flows during peak flow periods. A successful calibration of saturated zone boundary conditions and geological layers' vertical discretization, saturated hydraulic conductivities, drainage time constant, and leakage coefficient play a vital role to successfully quantify the SW and GW interactions. The above discussed differences between simulated and monitored GW levels and SW discharges are due to a combination of different sources of uncertainty: Structural (grid size, simplification of geology), input data (climate data), and parameter uncertainty (e.g., saturated hydraulic conductivity).

After, developing a calibrated process based coupled hydrological and hydraulic model, in fourth and final phase, available low frequency monitored flow and water quality data in combination with integrated hydrological and hydraulic modelling was used to represent the SW and GW hydrology and NO_3-N loads in Augraben River catchment. Lack of monitoring data in most of the catchment studies is a hurdle in water quality assessment.

In Augraben River catchment, a tributary of the Tollense river, discharge data was only available at catchment outlet. No measured discharges were available at Augraben River tributaries. GW levels were available at only two monitoring stations. It was assessed beforehand that these two monitoring locations could never be sufficient for the intended water quality assessment and variations. So available, but not used GW boreholes by local environmental protection authorities were selected (at least one borehole in each defined sub catchment) and monitored on monthly resolution for a period of a year and later on monitored data was used to calibrate the hydrological model.

In this study, integrated coupled hydrological and hydraulic model (MIKE SHE and MIKE 11) with limited available water quality data is used to estimate the hydrology and water quality variations. Based on coupled hydrological and hydraulic model results, we have successfully estimated the NO_3-N loads at catchment and sub-catchment scale by combining low frequency monitoring data with hydrological modelling. This enhances both, the explanatory strength of generally available and inexpensive quantitative hydrological data and the so far only qualitative status information from grab sampling. We related the responses of NO_3-N and P concentrations to the meteorological input and to the responses of simulated SW discharge and GW levels. These relations were used to estimate NO_3-N and P loads in study area. We have estimated the loads at SW monitoring stations and identified the GW contributions and the contribution of waste water treatment plants. In summer time, the measured load is found lower than the sum. The difference can be a rough estimate of NO_3-N transformations and plant uptake rates. The results of this study demonstrate that using the explanatory strength of quantitative hydrological data can significantly improve load estimates. Short-term dynamics of SW quality variations are not captured by common low-frequency grab sampling. Catchments characterized by rapid rainfall-runoff processes would require ideally continuous monitoring systems. However, in lowland river, dominated by base and intermediate flow, optimized grab sampling with few, well located hydrological measurements can provide meaningful data. The approach presented in this paper can be applied to improve quantitative and qualitative water management in similar hydrological conditions.

Key Contributions

An integrated hydrological model coupled with a hydrodynamic model was developed with intent to simulate the moderate climate lowland hydrology. In order to represent the surface and subsurface hydrology at a large scale, simplifications and assumptions were made in order to represent the UZ and SZ. Findings support the hypothesis that the hydrological processes in lowlands are dominated by SW and GW interactions. The key contribution of this study includes

- Comparison of empirical methods and physically based coupled distributed hydrological and hydraulic models to analyze hydrology and water balance in rural lowland river basins.
- Development of a technique for quantification of detailed mass balance and identification of critical areas in lowland catchments by using only the low frequency monitoring data from the local authorities.

Increased emissions due to land-use or so far unidentified point sources can be allocated. Further addition of a nutrient transport model is intended and will help to study the SW and GW quality under different land use scenarios.

Acknowledgement

I would like to express my deepest gratitude to **Prof. Dr.-Ing. habil. Jens Tränckner** for giving me an opportunity to work with this interesting and challenging theme, who allowed me to perform my PhD thesis under his supervision at the Institute of Water Management in University of Rostock. I cannot express enough thanks to my supervisor for his continued support, encouragement and motivation. His invaluable help of constructive suggestions has contributed to the success of this thesis. Working with him has been a great learning experience that I would cherish forever. I am sincerely thankful to him for being patient with me and being there to answer all my questions.

Besides my supervisor, I would like to thank all my colleagues who helped and supported me in completing the challenging tasks on time and this statement will be incomplete without mentioning the name of Dr. Christine Stapel, Ms. Frauke Kachholz and Ms. Ines Staeglich. Last but not the least, I want to take this opportunity to express my gratitude to my loving family and friends who have always supported and motivated me especially Malik Muhammad Shareef, Dr. Rabia Basri, Muhammad Saleem Akhtar, Noman Alvi, and Omar Mukhtar.

Dedication

This thesis is dedicated to the memory of my beloved mother late Sugrah Bibi. I will always love her.

Table of Contents

List of Figures

List of Tables

List of Symbols

ADCP	Acoustic doppler current profiler
BCs	Boundary conditions
COD	Chemical oxygen demand
DEM	Digital elevation model
DWD	Deutsche Wetterdienst (German Weather Services)
ET	Evapotranspiration
Eta	Actual evapotranspiration
Etp	Potential evapotranspiration
EU-WFD	European Water Framework Directive
GRASS	Geographic Resources Analysis Support System
GW	Groundwater
GWZ	Groundwater zone
GWMS	Groundwater monitoring station
HSPF	Hydrological simulation program–FORTRAN
LAI	Leaf area index
LUNG	State office for the environment, nature conservation and geology Mecklenburg-Vorpommern
MAE	Mean absolute error
MONERIS	Modelling Nutrient Emissions in River Systems
MPL	Maximum permissible limit
NN	Reference level
NO_3-N	Nitrate nitrogen
NO_2-N	Nitrite nitrogen
NH_4-N	Ammonium nitrogen
OL	Overland
Q_B	Base flow
Q_T	Total stream flow
P	Precipitation
PE	People equivalent

RD	Root depth
RMSE	Root mean square error
StALU-MS	State office for agriculture and environment Mecklenburg Lake District (StALU MS)
STDres	Standard deviation residuals
SW	Surface water
SWAT	Soil and water assessment tool
SWIM	Soil and water integrated model
SWTO	Surface water tributary outlet
SZ	Saturated zone
TP	Total phosphorous
UZ	Unsaturated zone
WWTP	Waste water treatment plant
α , β	Coefficient
q	Specific discharge

1. General Introduction

Nutrients are essential for all living organisms, animals and plants to grow. Problem is initiated when too much nitrogen and phosphorus emits into the environment usually from human activities [1]–[4]. The important causes of nutrient pollution include fertilizer runoff from agricultural fields, animal waste e.g. return flow from livestock activities and agricultural lands in Mecklenburg-Vorpommern [5]. High nutrient levels will result in higher growth of algae, as consequence algae will consume excessive amount of oxygen which is necessary for fish and other aquatic organisms to survive. Excessive algae in water bodies will make water cloudy and reduces the photosynthetic radiation to deeper water levels, which in turn lead to oxygen depletion there [6], [7]. Higher nitrate concentration levels in the groundwater (GW) can risk public health and environment [8]. Nutrient pollution also has effects on economy by affecting different sectors dependent on clean water, especially drinking water supply [9].

Agriculture nitrate diffuse pollution has increased considerably over the past few decades due to human activities related to the surplus use of both organic and synthetic fertilizers [2]. Over application of nitrogen N fertilizers to the crops in thin soils with steeper terrain can cause significant damages to the environmental ecosystem especially during wet seasons. Surplus nitrogen input is identified as a key contributor to the increased nutrient concentrations in surface, ground and coastal waters. World Health Organization (WHO) and EU-WFD defines 50 mg/L NO_3 or 11.3 mg/L NO_3-N as maximum acceptable concentration of nitrate in the drinking water and serves as a threshold for a "good ecological status" of a water body [10].

In Europe, agricultural activities continue to affect the SW and GW quality in terms of nitrate pollution. The excessive entry of nutrients in water bodies causes eutrophication and effects the ecology in rivers, lakes and coastal waters [11], [12]. In the Federal State of Mecklenburg-Vorpommern diffuse nutrient pollution is a major concern. Despite enormous efforts a large ratio of GW and surface water (SW) bodies still do not comply with the "good ecological status" according to the criteria of European Union water framework directive (EU-WFD) [13].

Multiple monitoring based studies have been made in north eastern lowlands of Germany to access the surface and subsurface water quality. In case of Germany, 18 percent of GW sampling sites exceeds the threshold value of 50 mg/l especially in areas with intensive agriculture activities [14]. In January 2017, Germany published its most recent report on nitrate pollution of waters ("Nitratbericht 2016", for the monitoring period up to and including 2014), in line with the obligations under the EU Nitrates Directive. The report underlines that agricultural fertilizers continue to negatively affect water quality in Germany, in particular GW. Almost one third of the monitoring points for GW quality show values above the limit value of 50 mg/l nitrate [5]. A study carried out in Zarnow basin in Mecklenburg-Vorpommern showed that 32 % of all the GW samples exceeds the permissible drinking water limit of 11.3 mg/l NO_3-N [15]. A study conducted in Mecklenburg-Vorpommern, states that 76% of the monitored SW have at least a significant pollution with nitrate and 40% with phosphate [16]. Most of these studies are based on extensive monitoring campaigns and requires excessive amount of human and financial efforts. Moreover, these study results are site specific and cannot be extrapolated to other catchments.

Multiple hydrological modelling studies have been made in north eastern lowlands of Germany with empirical and semi-distributed (e.g. SWAT and SWIM) models. Different mediums like GW, drainage, surface runoff and atmospheric deposition etc., have their different shares in transport of nitrates into the SW. A study done in Schleswig-Holsteins about the role of different sources of diffuse emission in Baltic Sea with a MONERIS (Modelling Nutrient Emissions in River Systems) model yielded that drainage (51 % of total load) and GW (39 % of total load) are the dominant pathways [17]. Nitrogen transport and reduction has been studied for the federal state of Mecklenburg-Vorpommern by Wendland et al. [18]. This study is comprised of a nutrient balance model, a water balance model (GROWA), a reactive nitrate transport model in soil (DENUZ) and a reactive nitrate transport model in GW (WEKU). Drainage was found to be a dominant pathway resulting in approximately 35% of the N transport leaching from the agriculture fields to the SW bodies. In federal state of Mecklenburg-Vorpommern, it is estimated that 54% of the nitrogen leaving the root zone is reduced before it reaches the SW bodies due to denitrification. This study has stated that model fits well to the observed data in larger catchments, while in case of smaller catchment the difference between observed and simulated values increase.

In north eastern Germany most of the studies are based on extensive monitoring in combination with empirical or semi distributed models. However, the low frequency monitoring data from local authorities in combination with distributed models have not been used so far. A study that just uses the monitoring data to study the hydrology and mass balance assessment can significantly improve the mass balance assessment and can successfully identify the areas requiring maximum attention to achieve WFD objectives. These kind of studies are also helpful as in case of limited or no financial assistance can provide better quality results. The current study is a combination of empirical methods and physically based fully distributed coupled hydrological and hydrodynamic models. This study uses available low-frequency monitored flow and water quality data in combination with empirical and integrated hydrological and hydraulic modelling to represent the SW and GW hydrology and NO_3-N loads in Tollense River catchment.

Nutrient levels in Tollense river and its tributaries is a concern for achieving good chemical status of Tollense river basin. Phosphorous and nitrogen are two significant nutrients resulting from organic and inorganic fertilizers through livestock grazing, pesticides and disinfectants. To develop more effective measures to reduce nutrient emissions, input, transport and transformation processes must still be better understood, especially for a higher spatial and temporal resolution. Hydrological and water quality modelling is important to understand the dynamics and as well as to identify the critical pollution levels in the water body in order to understand the dynamics and transport patterns of nutrients through surface and subsurface sources.

1.2.Aims and Objectives

The fundamental aim of this thesis is to develop an integrated approach to model the lowland hydrology in Tollense river basin. The objectives of this thesis are as follows:

1) Application of empirically based robust models to the available hydrological and water quality monitoring data to obtain preliminary findings regarding the GW and SW interactions and water quality;

2). Suitable modelling tool selection to describe the desired hydrological and hydraulic process in moderate climate lowland catchments based on the comparison of four process-based hydrological models;

3). Incorporation of all relevant processes and boundary conditions and to calibrate holistically the coupled hydrological and hydraulic model;

4). Detailed water balance estimation and quantification of GW and SW interactions;

5). Quantification of the meteorological effects on water balance components and the exchange of GW and SW during dry and wet hydrological years;

6). Estimation of the saturated zone represented by each water quality monitoring station in the study area and SW discharges at ungauged locations;

7). Representation of flow and water quality by combing low frequency monitored data with calibrated coupled hydrological and hydraulic model;

8). Assessment of the chosen approaches, namely of physically based distributed coupled models MIKE SHE and MIKE 11, and their ability to simulate lowlands with moderate climatic conditions.

1.3. Thesis Outline

Chapter 1 provides the problem statement and research objectives about the research study.

Chapter 2 presents the available monitoring data analysis by using simple parameterization techniques to assess the GW contribution to SW contamination in a north German low land catchment with intensive agricultural land use. SW and GW concentrations at the available SW and GW quality monitoring stations and quantification of critical nitrate, nitrite and ammonium loads during vegetation and non-vegetation periods in Augraben River catchment were estimated. Hydrograph separation techniques were used to divide the total flow into base flow and quick flow, and based on base flow calculations GW nitrate loads into SW were estimated. ***This chapter consist of the following publication***

Waseem, M., Koegst, T., & **Tränckner, J.** (2018). Groundwater Contribution to Surface Water Contamination in a North German Low Land Catchment with Intensive Agricultural Land Use. Journal of Water Resource and Protection, 10(03), 231.

https://doi.org/10.4236/jwarp.2018.103014

Chapter 3 presents the review study focused mainly on the selection of an appropriate modelling tool to quantify the hydrology and water quality in lowland catchments and explains and compares different widely used integrated water modelling tools, their intended use, parameters and processes, limitations, strengths and their application to particular conditions. The selected models differ in the degree of complexity in explaining the catchment spatially, temporally and also the complexity of their representation of the physical, chemical and biochemical processes involved in forecasting the fate and transport of nutrients. This report allows researchers to make informed decisions when selecting a suitable model to predict hydrology and water quality in lowland catchments. ***This chapter consist of the following publication***

Waseem, M., Kachholz, F., & **Traenckner, J.** (2018). Suitability of common models to estimate hydrology and diffuse water pollution in North-eastern German lowland catchments with intensive agricultural land use. Frontiers of Agricultural Science and Engineering, 5(4), 420-431.

https://doi.org/10.15302/J-FASE-2018243

Chapter 4 presents the suitability of a coupled hydrologic (MIKE SHE) and hydraulic (MIKE 11) model to simulate SW and GW hydrology in a typical North-Eastern Germany lowland catchment. In this study a detailed water balance and seasonal dynamics of GW levels and SW discharges were estimated. ***This chapter consist of the following publication***

Waseem, M., Kachholz, F., Klehr, W., & **Tränckner, J.** (2020). Suitability of a Coupled Hydrologic and Hydraulic Model to Simulate Surface Water and Groundwater Hydrology in a Typical North-Eastern Germany Lowland Catchment. Applied Sciences, 10(4), 1281.

https://doi.org/10.3390/app10041281

Chapter 5 presents the representativeness of GW quality monitoring results in the context of nitrate loads. Estimation of the saturated zone represented by each water quality monitoring station in the study area and possible new locations of boreholes for GW quality monitoring were estimated. Based on detailed water balance estimation and quantification of GW and SW interactions, quantification of GW nutrient loads and estimation of land-use impacts on GW quality were estimated. This chapter consist of the following publication

Waseem, M., Schilling, J., Kachholz, F., & **Tränckner, J.** (2020). Improved Representation of Flow and Water Quality in a North-Eastern German Lowland Catchment by Combining Low-Frequency Monitored Data with Hydrological Modelling.

https://doi.org/10.3390/su12124812

Chapter 6 presents the discussion about the combined results of the current study

Chapter 7 presents the proposed directions for the future research of this study

References

[1] Zhang, X.; Davidson, E.A.; Mauzerall, D.L.; Searchinger, T.D.; Dumas, P.; Shen, Y. Managing nitrogen for sustainable development. Nature 2015, 528, 51–59.

[2] Food and Agriculture Organization (FAO). Nitrogen Inputs to Agricultural Soils from Livestock Manure; New Statistics: Rome, Italy, 2018.

[3] UNWater. Progress on AmbientWater Quality. Piloting the Monitoring Methodology and Initial Findings for SDG Indicator 6.3.2. 2018. Available online: https://www.unwater.org/publications/progress-on-ambientwater- quality-632/ (accessed on 10 September 2020.

[4] Bechmann, M.; Stålnacke, P. Agricultural nitrogen and phosphorus pollution in surface waters. In Oxford Research Encyclopedia of Environmental Science; Oxford University Press: Oxford, MS, USA, 2019.

[5] Nitratbericht 2016 Gemeinsamer Bericht der Bundesministerien für Umwelt, Naturschutz, Bau und Reaktorsicherheit sowie für Ernährung und Landwirtschaft.

[6] Chislock, M. F., Doster, E., Zitomer, R. A., & Wilson, A. E. (2013). Eutrophication: causes, consequences, and controls in aquatic ecosystems. Nature Education Knowledge, 4(4), 10.

[7] Misra, O. P., & Chaturvedi, D. (2016). Fate of dissolved oxygen and survival of fish population in aquatic ecosystem with nutrient loading: a model. Modeling Earth Systems and Environment, 2(3), 112.

[8] Sousa, M.R., Rudolph, D.L. and Frind, E.O. (2014). Threats to groundwater resouces in urbanizing watersheds: The waterloo Moraine and beyond. Canadian Water Resources Journal, 39:2.

[9] The Effects: Economy. Reterived from https://www.epa.gov/nutrientpollution/effects-economy.

[10] Verordnung zum Schutz der Oberflächengewässer (Oberflächengewässerverordnung; OGewV) vom 20. Juni 2016. In: BGBI., 2016, I, S. 1 373). Available online: https://www.gesetze-im-internet.de/ogewv_2016/OGewV.pdf (accessed on 3 May 2020).

[11] European Commission. Agriculture and Sustainable Water Management in the EU;

Commission Sta_ Document; European Commission: Brussels, Belgium, 2017. Available online: https://circabc.europa.eu/sd/a/ab_972e- 203a-4b4e-b42e-a0f291d3fdf9/SWD_2017_EN_V4_P1_88.

[12] European Commission. Report from the Commission to the Council and the European Parliament on the Implementation of Council Directive 91/676/EEC Concerning the Protection of Waters Against Pollution Caused by Nitrates from Agricultural Sources.

[13] He, B.; Kanae, S.; Oki, T.; Hirabayashi, Y.; Yamashiki, Y.; Takara, K. Assessment of global nitrogen pollution in rivers using an integrated biogeochemical modelling framework. Water Res. 2011, 45, 2573–2586.

[14] Sundermann, Greta; Wägner, Nicole; Cullmann, Astrid; von Hirschhausen, Christian R.; Kemfert, Claudia (2020): Nitrate pollution of groundwater long exceeding trigger value: Fertilization practices require more transparency and oversight, DIW Weekly Repor.

[15] Brook Zarnow gauging station Zarnow basin, Germany. Retrieved from http://ne-friend.bafg.de/servlet/is/17796/Zarnow.pdf

[16] Koch F (2014) Diffuse Nährstoffbelastungen in Oberflächengewässern und im Grundwasser, 19. Gewässersymposium, 19.11.2014 Güstrow.

[17] Rostock. Meeresbiolog. Beitr (2004). Nährstoffausträge in die Ostsee aus diffusen Quellen Mecklenburg-Vorpommerns und Schleswig-Holsteins Nutrient emissions from diffuse sources of Mecklenburg-West Pomerania and Schleswig-Holstein to the Baltic Sea.

[18] Wendland F., Keller L., Kuhr P., Kunkel R., Tetzlaff B. (2015) Regional differenzierte Quantifizierung der Nährstoffeinträge in das Grundwasser und in die Oberflächengewässer Mecklenburg-Vorpommerns unter Anwendung der Modellkombination GROWADENUZ-WEKU-ME.

2. Empirical Source Separation of Nitrate in Surface Water Runoff

Based on the research article:

Waseem, M., Koegst, T., & Tränckner, J. (2018). Groundwater Contribution to Surface Water Contamination in a North-Eastern German Low Land Catchment with Intensive Agricultural Land Use. *Journal of Water Resource and Protection, 10*(03), 231.

https://doi.org/10.4236/jwarp.2018.103014

Abstract: The contribution of groundwater (GW) to the nitrate loads in surface water (SW) was exemplarily studied for the River Augraben with a catchment area of 89.9 km^2, located in North-Eastern Germany. The study uses available GW and SW quality data in order to develop a relationship between SW and GW in the Augraben River catchment. The calculated ratio of base flow varies between 40% to 80% using various hydrograph separation methods. Results on the basis of monitoring data and hydrograph separation in quick flow and base flow showed that during winter periods, high SW concentrations are observed in parallel to the periods of high GW flows. A strong correlation exists between the observed SW and GW concentrations. These findings also coincided with the measured high NO_3-N concentrations during non-vegetation period due to low nitrogen uptake by plants. Measured GW concentrations in the catchment differ strongly, depending on land-use with elevated concentrations in agricultural areas in comparison to monitoring stations in grassland and forest areas. At the GW monitoring station, "Au II Alt Kentzlin," NO_3-N concentrations exceeds twice the maximum permissible limits (MPL) of 11.3 mg/l NO_3-N). High NH_4-N concentrations at GW monitoring station "Kriesow" can possibly due to excessive application of manure. Drainage and interflow proved to be a significant contributor with 55-65% of total SW NO_3-N loads.

Keywords: Base flow separation, Diffuse pollution, Drainage and interflow, Groundwater nitrate, River Augraben

2.1. Introduction

Agriculture related pollution has attracted increased attention worldwide over the past 40 years due to its consequences on water quality [1, 2]. Nitrogen inputs in intensive agricultural catchments have been identified as a significant factor in the trends of increased nutrient concentrations in the surface, ground, and coastal waters [3]. Inputs from effluents and atmospheric deposition are also important. Nitrate is the most frequently introduced pollutant in GW systems [4]. Pollution of GW and SW by diffuse sources is a severe problem in the European Union (EU) [5].

Use of fertilizer for agricultural production enhancement continues to negatively affect the overall SW and GW quality in Germany [6]. Nitrate in GW can originate from the direct application of mineral fertilizer or via the transformation from ammonia, either from mineral fertilizers or manure from animal husbandry. Ammonia is as a cation in tendency better retained in the soil. However, its ecotoxic relevance is even higher due to the high oxygen demand when transformed to nitrate and the acute toxicity of NH_3 [7, 8]. Ammonia toxicity in aquatic systems is of particular concern in regions of high human habitation with insufficient wastewater treatment facilities [9-12]. The maximum acceptable concentration of nitrate for potable water according to the World Health Organization (WHO), is 11.3 mg/l NO_3-N or 50 mg/l NO_3 [13]. The same concentration is defined as a threshold for the good chemical status of GW according to the European Water Framework Directive (EU-WFD). Even below this threshold, nitrate is highly relevant because of its eutrophication potential.

In 2010 the total nitrogen input in the Baltic Sea through water and airborne sources was 977,000 tons of nitrogen. Manure leaching accounts for 60-70% of the total diffuse and more than half of the waterborne inputs in the Baltic Sea [14]. Accordingly, pollution of GW and SW through diffuse sources is a significant concern in the Federal State of Mecklenburg-Vorpommern (MV) in North-Eastern Germany and ultimately in the Baltic Sea. Objectives to reduce eutrophication were set in the Baltic Sea Action Plan (BSAP), implemented in 2007 [15], and reviewed in 2013 [16]. In the 5th Baltic Sea pollution load compilation (PLC5.5), a 9% reduction in total nitrogen loads in the Baltic Sea was estimated from the period between 1997 to 2003, but it is also observed that a further reduction of 14% is still required [17]. Analyzing the monitoring data from 1970 to 2000, Saaltink et al. [18] found that the reduced nitrogen loads are not evenly distributed but display considerable spatial variation and are related to the socio-economic developments within the Baltic Sea Basin. The estimated nitrogen (N) reduction of 26% is further required in the Baltic Sea [17], out of which 5000 t/a N shall be reduced by the state MV. Specific estuaries and coastal waters may require even higher specific abatements in order to protect coastal and transitional water ecosystems and comply with the objectives of the EU-WFD [19].

Wendland et al. [20] found drainage as a dominant pathway resulting in approximately 35% of the N transport leaching from the agriculture fields to the SW bodies in the Federal state of MV. It is estimated that only 54% of the N leaving the root zone is reduced before it reaches the SW bodies due to denitrification. In January 2017, Germany published its report on nitrate pollution of waters ("Nitratbericht 2016" for the monitoring period up to and including 2014), in line with the obligations under the EU Nitrates Directive. The report underlines that agricultural fertilizers continue to affect water quality in Germany, particularly the GW. Almost one-third of the GW quality monitoring stations showed values above the threshold value of 50 mg/l NO_3. In the case of MV, a study carried out in the Zarnow basin showed that 32 % of all the GW samples exceeds the threshold value of 11.3 mg/l NO_3-N [21]. Another study carried out in MV, states that 76% of the monitored SW have at least a significant pollution with nitrate and 40% with phosphate [22]. Different pathways like GW, drainage, surface runoff, and atmospheric deposition etc., have their different shares in the transport of nitrates into the SW. A study carried out in MV and Schleswig-Holsteins about the role of different sources of diffuse emission in Baltic Sea shown in **Figure 2.1**, yielded that drainage (51 % of total load) and GW (39 % of total load) are the dominant pathways [23].

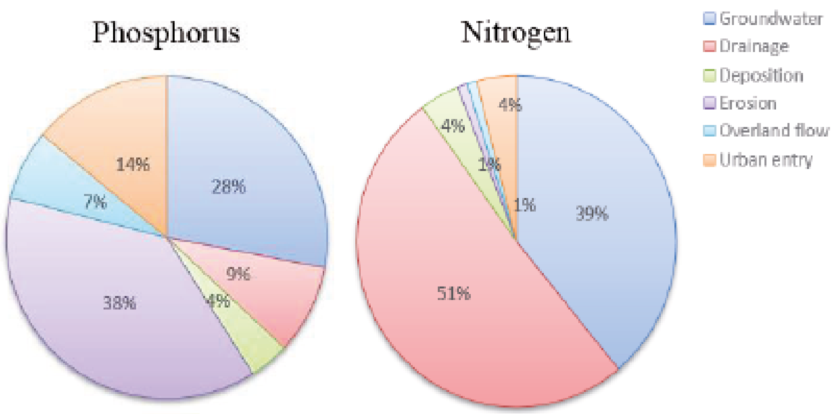


Figure 2.1 Pathways contributing to eutrophication of the Baltic Sea [23].

In order to reduce GW pollution, several approaches are available to predict and estimate nitrate contamination from different sources. One approach is to apply solute leaching models [13] which are difficult to calibrate and their boundary conditions cannot be easily satisfied in complex land-use systems especially in non-uniform strata [24]. An easier and more convenient method is to make the comparison and integration of SW and GW quality data from monitoring networks. Though these approaches do not describe the processes itself but can combine available data with adapted conceptual approaches to get reliable estimates of the pathways. In this study, GW flow in a characteristic lowland river, the Augraben, was estimated by using hydraulic gradient method and different hydrograph separation techniques. The hydraulic gradient method is based on aquifer characteristics and the measured hydraulic gradients in the river and nearby available boreholes. This method works well in local GW fluxes near to the gauging stations. However, it does not always represent reasonable estimations of GW flow in longer reaches. The hydrograph separation method takes into account the time series of river discharge and then divide it into base flow and quick flow [25]. Since separation methods are no process-based models, the interpretation of base flow and quick flow is often not distinct, especially concerning the interflow (e.g., drainage). This study is mainly focused to develop and apply a method to assess the contribution of GW to the nitrogen loads in SW based on available monitoring data.

The research objectives of this study include i) Comparison of the SW and GW concentrations at the available GW and SW quality monitoring stations; ii) Quantification of critical NO_3-N, NO_2-N and NH_4-N loads during vegetation and non-vegetation periods in Augraben River catchment; iii) Quantification of GW contribution to calculated NO_3-N loads in the Augraben. In order to achieve these objectives, available data is analyzed at each SW and GW quality monitoring station. The main emphasis of this study is on nitrogen compounds introduced by GW into the Augraben (NO_3-N, NO_2-N, NH_4-N).

2.2. Materials and Methods

2.2.1. Study Area

Figure 2.2, shows the Augraben River catchment (89.9 km^2) located in North-Eastern Germany. Land use was estimated by the aerospace images obtained from the "Rapid Eye Science Archive" website [26]. The study area consists of 2.22% water, 2% settlements, 18% forest area, 75% arable and grassland while 3% miscellaneous. The catchment area is mainly used for agriculture and is equipped with artificial drainage. The tile drainage was established in the study area in the 60s and 70s. It was not possible to obtain the tile drainage maps of the farms due to data privacy rights of the farmers. The geology in the study area is very heterogeneous and consists mainly of glacial deposits of fluvial sand and glacial till. Due to extreme geological heterogeneity, a large and diverse system of unconfined and confined aquifers with different flow directions and residence times exists in the lowlands located in north-eastern Germany.

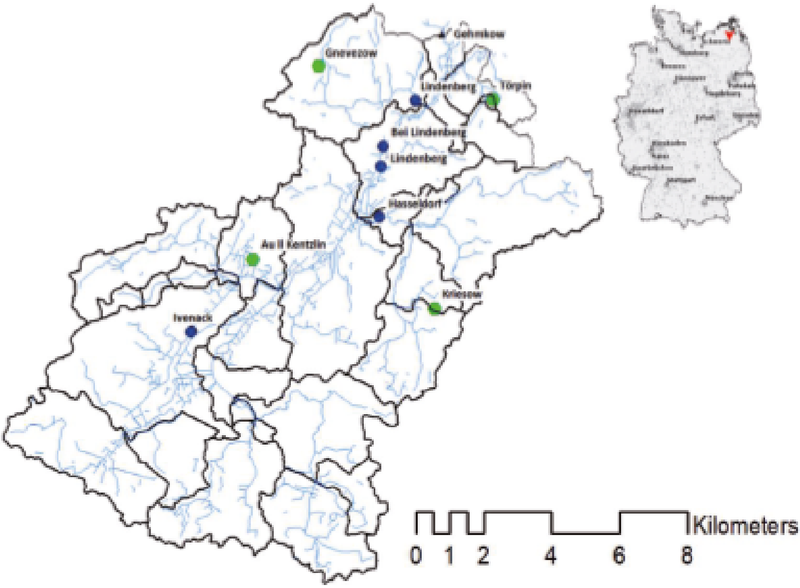


Figure 2.2 (Right) Location of River Augraben catchment in Germany. (Left) Location of GW quality monitoring stations (Green), SW quality monitoring stations (dark blue), and small rivers (light blue) in the catchment area.

2.2.2. Data Acquisition and Processing

GIS was used for the effective management of GW quality data [27-30]. A digital elevation model (DEM) was used to predict the surface flow based on the topography of the catchment. Artificial drainage was constructed in Arc-GIS based on the lowest points on the DEM. Land-use classification was performed in Arc-GIS. Plausible drainage was constructed based on the topography using Arc hydro tools in GIS. The constructed drainage could be different from the actual artificial drainage system installed in the study area but gives a rough idea of drainage flow directions.

2.2.2.1. Water Quality Data

Only 3 GW boreholes are in use by Landesamt für Umwelt, Naturschutz und Geologie Mecklenburg-Vorpommern (LUNG-MV) for GW quality monitoring in the study area. The monitoring interval for the GW quality assessment is every six months. **Table 2.1**, shows the availability of GW quality data from 2011 to 2014 for the available GW quality monitoring stations in the study area.

Table 2.1 Availability of GW quality data for the available monitoring stations

Station Name	2011		2012		2013		2014		Sampling Interval
Kentzlin	-----	Dec	April	Oct	April	Oct	April	Oct	6 months
Törpin	Aug	Dec	April	Oct	April	Oct	April	Oct	
Kriesow	Aug	Dec	April	Oct	April	Oct	April	Oct	

The Augraben River catchment was divided into four sub-catchments named as "Lindenberg" (yellow), "Hasseldorf" (Green), "Grischow" (light green) and "Ivenack" (grey) based on groundwater contours, SW, and GW quality monitoring stations as shown in **Figure 2.3**. As there was no GW data available in zone A and C, a measurement campaign was launched and GW quality data was collected monthly at Gnevezow (Zone A) for six months from January 2017 till June 2017. GW samples were collected and analyzed on-site for NO_3-N, NO_2-N, and NH_4-N concentrations. In case of zone C, no boreholes were available in that area. As a result, GW concentrations in the nearest zone B were used. The reason behind this assumption was that the land use in zone B and zone C is similar having similar assumed fertilizer application rates.

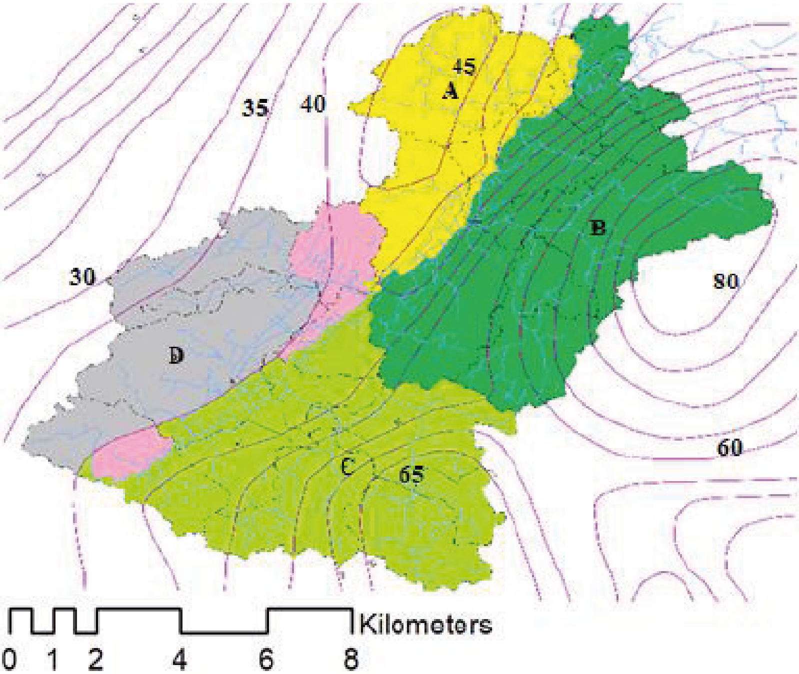


Figure 2.3 Augraben River catchment divided into Zone A (yellow), B (green), C (light green), and D (grey).

SW quality monitoring in the study area is organized and managed by state authorities. SW quality data at a particular sub-catchment outlet represent and characterize the integrated impact of that whole particular sub-catchment. SW quality data was collected and analyzed at each of the available SW quality monitoring station in order to identify the critical locations in terms of nitrate pollution and also to access the water quality variations against the flow in these areas. **Table 2.2**, shows the SW quality data at available monitoring stations with their sampling interval. SW quality and discharge data were analyzed at the gauge station installed near Gehmkow, representing the outflow of almost 85% of the whole River Augraben catchment. Flow at each outlet of four zones A, B, C, and D was estimated from the average flow data provided by Biota [31]. Available flow data at Augraben River catchment outlet is shown in **Figure 2.4**.

Table 2.2 Surface water quality monitoring stations with a monthly sampling interval

Station Name	2011	2012	2013	2014	2015
Lindenberg	•	•			
Hasseldorf		•			•
Ivenack	•			•	
Bei Lindenberg			•	•	•

Hydrograph separation was done at Bei Lindenberg where maximum observed data was available to estimate the impact of GW on NO_3-N loads in the Augraben. GW flow was separated by combining hydrograph separation and hydraulic gradient method to quantify the impact of GW on SW NO_3-N concentrations.

2.2.3. Flow Data at Gehmkow Gauging Station

Available daily average discharge data was collected for Gehmkow gauging station (Augraben river catchment outlet) for the period from 2009 to 2015. The flow hydrograph in **Figure 2.4** shows that high flows occur during the winter seasons in comparison to the observed flows during the summer. Flow data was separated into quick flow and base flow in order to quantify the GW inflow and its role in the overall NO_3-N loads in SW.

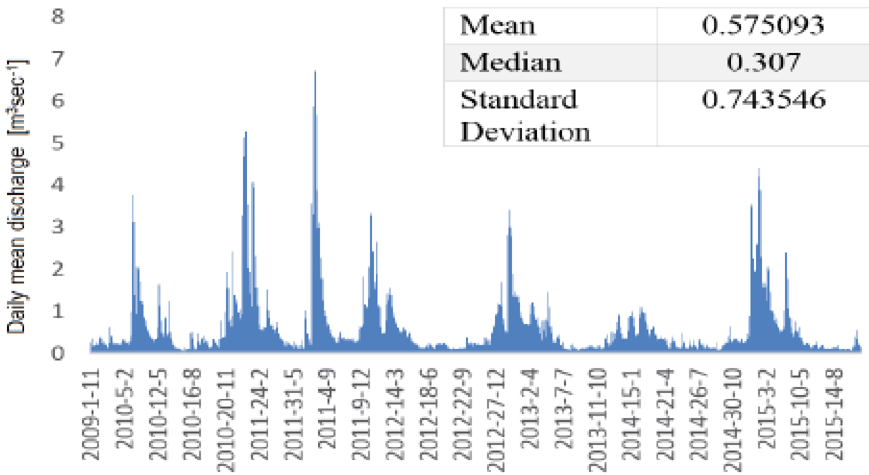


Figure 2.4 Daily flow hydrograph at Gehmkow gauging station from 2009-2015.

2.3. Hydrograph Separation with Module BFI+3.0

The main objective of hydrograph separation is to divide the flow hydrograph into quick flow (a short term response to a rainfall event) and base flow (delayed GW flow). The applied methods can be categorized as (i) graphical methods (ii) filtering methods (iii) frequency analysis method. For hydrograph analysis and its separation, different tools and programs are available [32, 33]. In this study, the base flow index module BFI+3.0 was applied. BFI+3.0 uses filtering methods to analyze and separate the base flow from the total flow.

Hall [34], defined the delayed portion of flow which originates from GW and other sources as base flow. Base flow time series represents the GW dynamics in a particular catchment. Proportion of base flow from the total flow as an index can represent the ability of a catchment to store and discharge water during the dry periods. A higher value of base flow index shows that the catchment has a stable flow regime and can sustain even during the prolonged dry periods [32].

2.3.1. Filtering methods of hydrograph separation

Filtering methods are the most popular ways of streamflow hydrograph separation into its components as base flow and direct flow. These methods do not have any hydrological and physical basis, but can provide a reasonable estimation of base flow. With this principle algorithm, it separates base flow as a low-frequency signal and direct flow as a high-frequency signal. The results of filtering methods are comparable to graphical techniques [35]. Hydrograph separation methods used in this study are described as follows.

2.3.1.1. Hydrograph separation by Lyne & Hollick

Following is the algorithm given by Lyne and Hollick [36]

$$Q_{b(i)} = \alpha Q_{b(i-1)} + \frac{1-\alpha}{2}\left(Q_{T(i)} + Q_{T(i-1)}\right) \qquad [1]$$

Where; Q_b = Base flow, Q_T = Total stream flow, i = time step number, α = coefficient (0,925) [37].

2.3.1.2. Hydrograph separation by Nathan and McMohan

Equation [1] was later modified by Nathan and McMohan [38] as follows

$$Q_{d(i)} = \alpha Q_{d(i-1)} + \beta(1+\alpha)\left(Q_{T(i)} + Q_{T(i-1)}\right) \qquad [2]$$

Where, Q_d = Direct flow ($Q_d \geq 0$) for the initial time step, Q_T = Total stream flow, α = coefficient (0.925) [37], β = coefficient (0.5) [39]. By inserting the values of α and β in equation [2]

$$Q_{d(i)} = 0.925Q_{d(i-1)} + 0.9625(Q_{T(i)} + Q_{T(i-1)}) \quad [3]$$

2.3.1.3. Hydrograph separation by Chapman

Hydrograph separation techniques known as Chapman method was used and is as follows

$$Q_{d(i)} = \frac{3\alpha-1}{3-\alpha}(Q_{d(i-1)}) + \frac{2}{3-\alpha}(Q_{T(i)} + Q_{T(i-1)}) \quad [4]$$

Where; α = coefficient (0.925) [37].

2.3.2. GW Inflow in River Augraben by Hydraulic Gradient Method

In parallel to hydrograph separation techniques, flow through an unconfined aquifer to the surface water system was estimated by using the hydraulic gradient method. Its application requires the assumption of the following conditions (i) flow velocity is proportional to the tangent of the hydraulic gradient instead of sine. (ii) flow is considered horizontal and uniform throughout the vertical section. For unidirectional flow, specific discharge is given below

$$q = -kh\frac{dh}{dx} \quad [5]$$

Where K = hydraulic conductivity, h = water table height above the reference point and x = direction of flow. **Figure 2.5**, below shows the GW flow to the stream in an unconfined aquifer [25].

On the basis of GW table fluctuations based on the logger data from 2010 to 2015 provided by LUNG-MV at six boreholes in the study area, hydraulic gradient method was applied, and average GW velocities were calculated in all four zones A, B, C, and D, as 0.35 m/day, 0.4 m/day and 0.057 and 0.04 m/d respectively. Only upper unconfined aquifer was considered to be contributing in the Augraben based on the geological data of borehole logs provided by LUNG-MV.

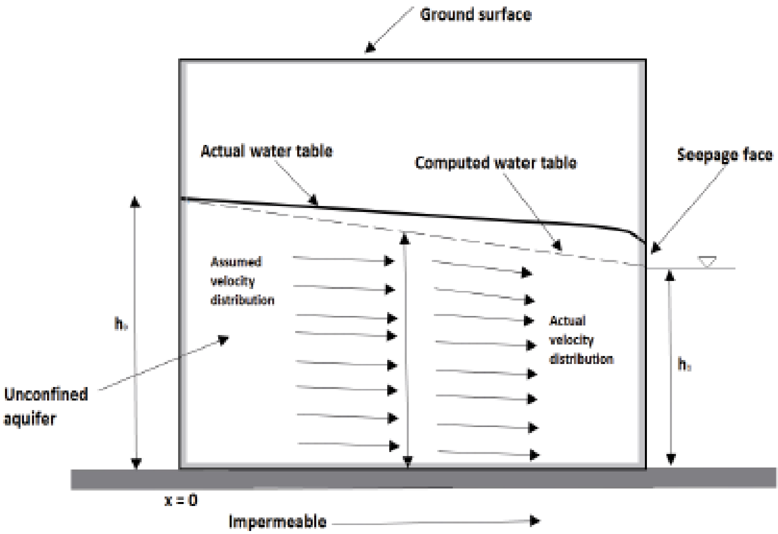


Figure 2.5 Schematic diagram of GW contribution to the streams in an unconfined aquifer [25].

2.3.3. Data Processing

Comparison of SW and GW quality data obtained from monitoring locations in a lowland artificially drained catchment was used to get an insight into the SW and GW interactions. GW quality concentrations for all the available monitoring stations were analyzed for NO_3-N, NO_2-N, and NH_4-N concentrations and trends have been established. Due to the lack of permanent monitoring locations, GW concentrations were calculated in the catchment area based on average concentrations for the spatial extent of homogeneous areas within the catchment. SW quality and discharge data was analyzed at the gauge station installed near Gehmkow.

2.4. Results

2.4.1. Hydrograph Separation and Role of drainage

2.4.1.1. Hydrograph Separation

Hydrograph separation was carried out with different mentioned methods and found that CAM estimates the base flow 50-60% lower than the other methods throughout the considered period with the least value of standard deviation. In the case of LMM, N&M,

L&H, and FIM, these methods calculated that around 70-80% flow in Augraben is the sum of base flow and interflow. In contrast, the calculated GW flow applying hydraulic gradient method with 6-8% is significantly lower throughout the study period.

2.4.1.2. Drainage Estimation

This difference between hydraulic gradient method and other empirical base flow estimation methods can be explained with delayed interflow from drainage. As in BFI+3.0, all the defined methods do not explicitly consider interflow and drainage effects, and the derived base flow may be interpreted as the sum of interflow and GW flow depending on the parametrization and the actual interflow characteristics of the regarded system. The hydraulic gradient method is based on the GW and river water levels and can quantify the GW infiltration. So the difference between both approaches can be interpreted as an estimate for interflow mainly caused by the drainage system installed in the catchment. The relatively constant value of base flow by hydraulic gradient method is possibly due to very flat GW levels in the Augraben River catchment and water levels in the Augraben, as shown in **Figure 2.6**. Overall analysis showed that the local minimum method overestimates the base flow during high flows, while Nathan and McMohan's method remained stable during high and low flows. Local Minimum method, Nathan and McMohan, and Lyne and Hollick method showed a similar amount of base flow percentage from total streamflow, while Chapman logarithm yields a rather low base flow. **Figure 2.7** shows the percentages of base flow from the total flow. By taking into consideration the difference, drainage and interflow was estimated to contribute 50% of the total flow in the Augraben.

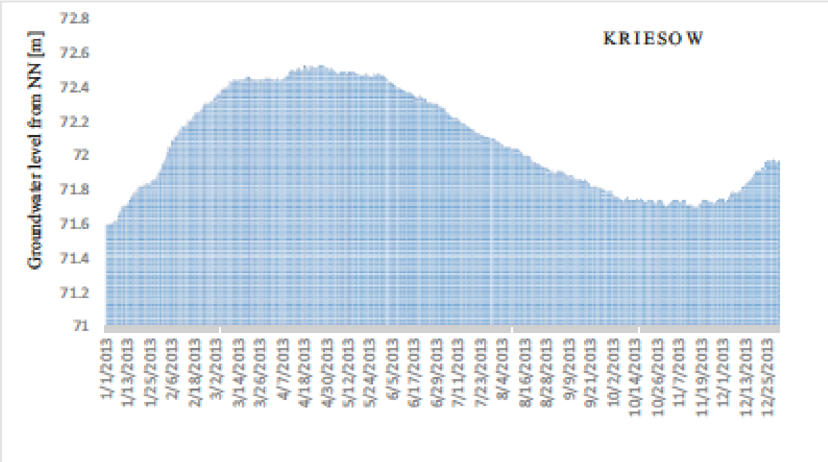


Figure 2.6 GW levels from reference point at Kriesow during 2013

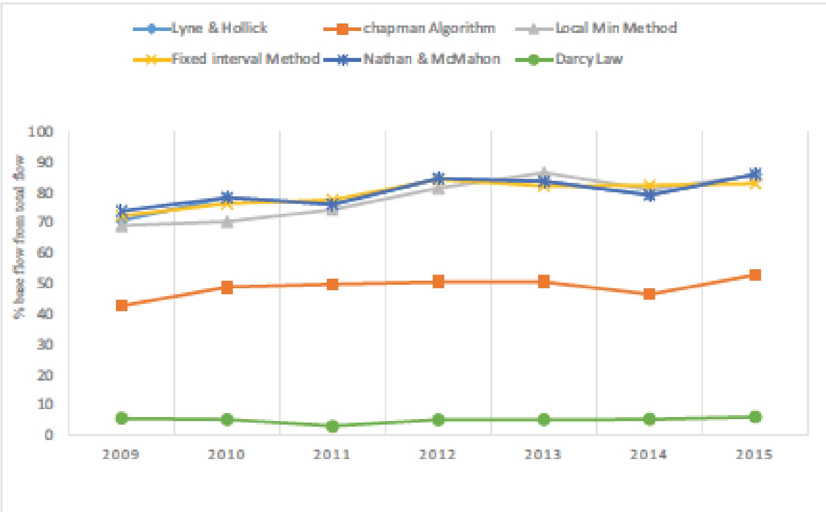


Figure 2.7 Comparison of percentage of base flow separated from total flow by different methods.

2.4.2. SW NO_3-N Loads during Vegetation and Non-Vegetation Periods

Vegetation period in North-East Germany was considered on average from April till October every year [40]. High NO_3-N loads were observed during the non-vegetation periods between November and February, as shown in **Figure 2.8**. It can be explained that during the non-vegetation period, there is no plant uptake of nitrogen compounds from the soil results in higher leaching of nutrients than in summer. Moreover, higher base flows in winter seasons result in a higher contribution of GW to total SW NO_3-N loads. Fertilization rates and their application times play a vital role as the applied fertilizers at the harvesting times will be available for leaching during the winter season.

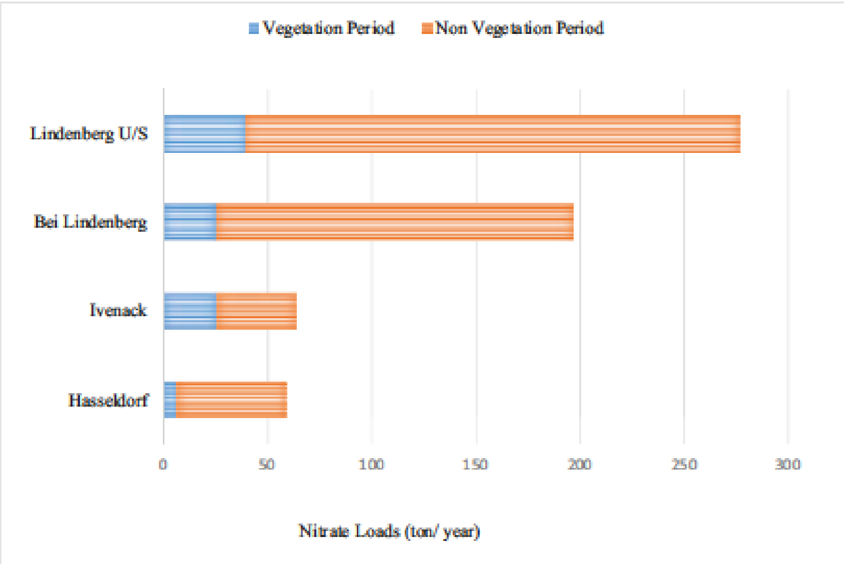


Figure 2.8 Calculated NO_3-N loads at all the available surface water quality monitoring stations during vegetation and non-vegetation period.

2.4.3. Role of GW in SW NO_3-N Loads

GW quality data was collected and analyzed at available GW quality monitoring stations. GW quality monitoring station named "Törpin" is situated in a residential area, while "Kriesow" and "Au Alt II Kentzlin" are located in the agriculture area. In the case of NO_3-N concentrations, high values were observed at Au II Alt Kentzlin, while in case of the other two stations NO_3-N concentrations were relatively low. NO_3-N concentrations at GW quality monitoring station Au II Alt Kentzlin located in zone D exceeds twice the permissible limits and also contribute maximum NO_3-N load in the River Augraben as shown in **Figure 2.9**. NO_2-N concentrations shown in **Figure 2.10**, shows a gradual decrease except in the year 2013 were all three stations showed a higher concentration. NH_4-N is an indicator of the application of animal manure in agricultural areas. Application of liquid manure is by law limited to the vegetation period from March to October. **Figure 2.11** shows observed increased and seasonally changing concentrations of NH_4-N at the GW quality monitoring point in Kriesow shows higher concentrations in summer than in winter. On the other two GW quality monitoring stations in the study area, named as Törpin and Au ll Kentzlin, NH_4-N concentrations are very low and stable during the period between 2011 to 2014. Monitored data reflect the typical agricultural practices in the study area.

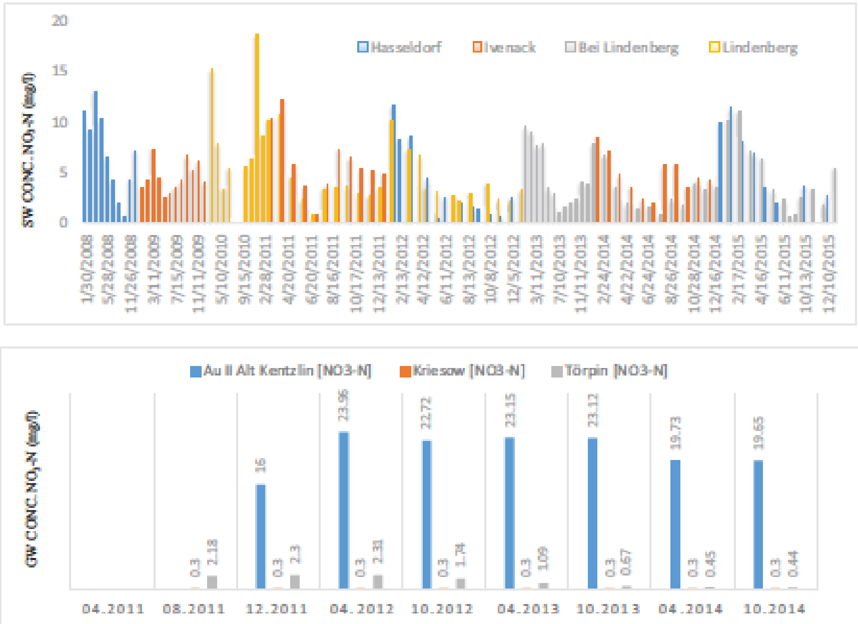
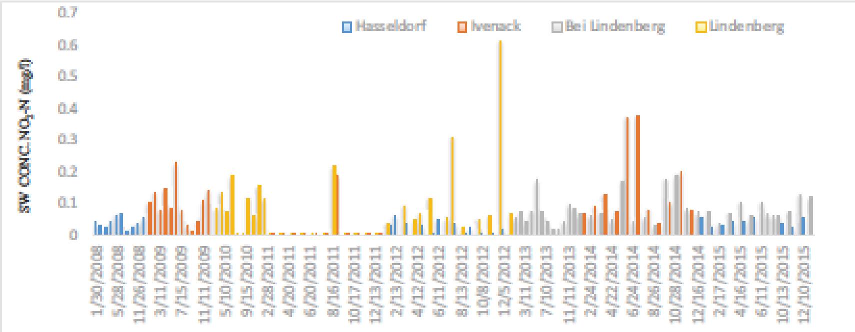


Figure 2.9 Observed NO_3-N concentrations in groundwater (down) and surface water (up) at water quality monitoring stations in Augraben River catchment.



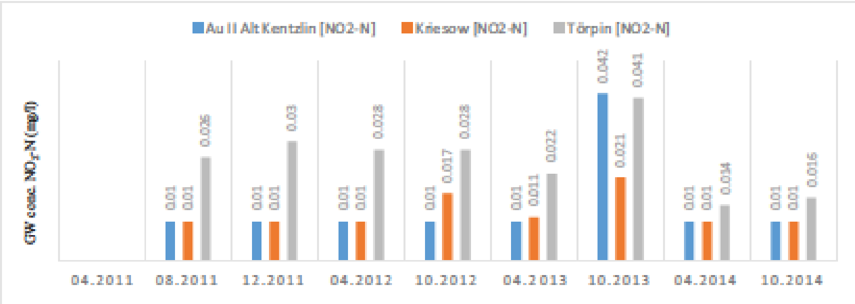
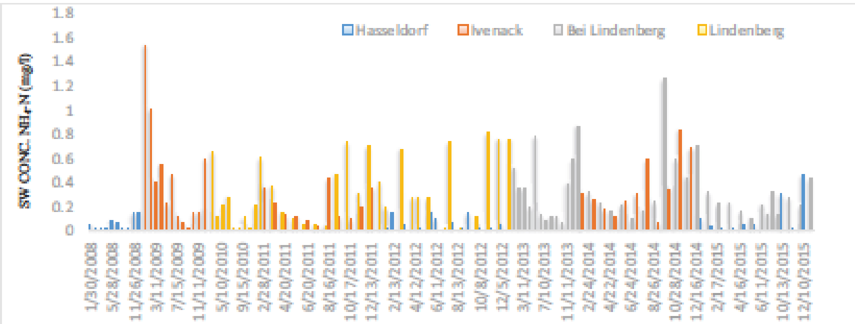


Figure 2.10 Observed NO2-N concentrations in groundwater (down) and surface water (up) at water quality monitoring stations in Augraben River catchment.



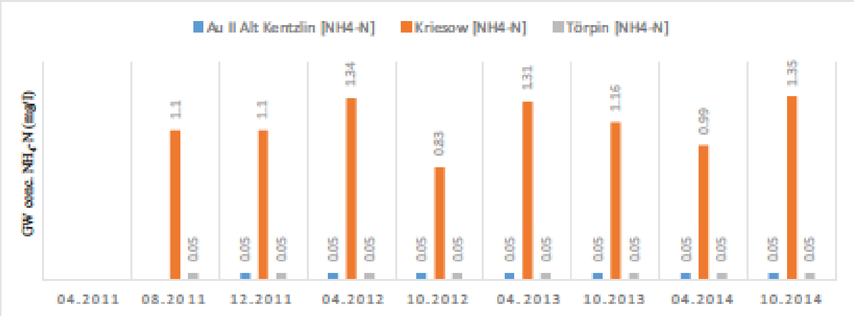


Figure 2.11 Observed NH_4-N concentrations in groundwater (down) and surface water (up) at water quality monitoring stations in Augraben River catchment.

In case of Kriesow as shown in **Figure 2.11**, the overall situation is not good as WHO [41, 42] does recognize odour effects at a concentration of ammonium nitrogen at 1.5 mg/L and taste effects at 35 mg/L. NH_4-N can change into free ammonia, which is toxic for fish and aquatic life based on pH and temperature. Ammonia is toxic to fish and other forms of aquatic life at very low concentrations. Accordingly, the German order for surface freshwater systems [43] defines a target value for NH_4-N of 0.04 mg/l. Higher SW nitrate loads were observed in Zone D, while zone A and B showed on average lower values of NO_3-N loads as it can be correlated with GW quality as in case of GW loads zone D showed higher loads in comparison to other zones as shown in **Figure 2.12**. GW loads of each zone were calculated using the hydraulic gradient method.

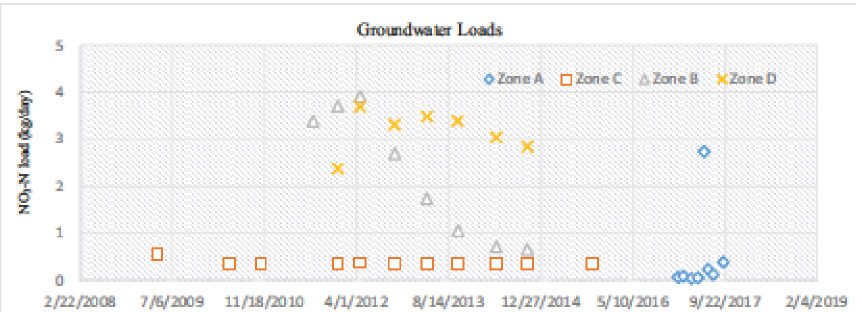


Figure 2.12 GW NO_3-N loads in zone A, B, C and D in study area

2.4.4. Overall SW Quality in Gehmkow Catchment

Figure 2.13 shows the daily average discharge, base flow and NO_3-N concentrations at Bei Lindenberg from 2011 to 2015 in River Augraben catchment. Discharge data shows a strong correlation between rainfall and river water discharge, and high concentrations were observed after periods of rainfall. Quick drainage of the catchment is due to the presence of an artificial drainage network in the area. GIS was used to identify the critical GW pollutant areas based on measured concentrations in the GW. GW loads calculated from estimated base flow calculations from different base flow separation methods and measured GW concentrations resulted that the GW contributes around 25-45% of the total loads in Augraben while the remaining 55-75% is probably through the other sources such as drainage system, overland flow, and atmospheric deposition. This study also showed that management and monitoring of GW and SW should be done in high temporal and spatial resolution.

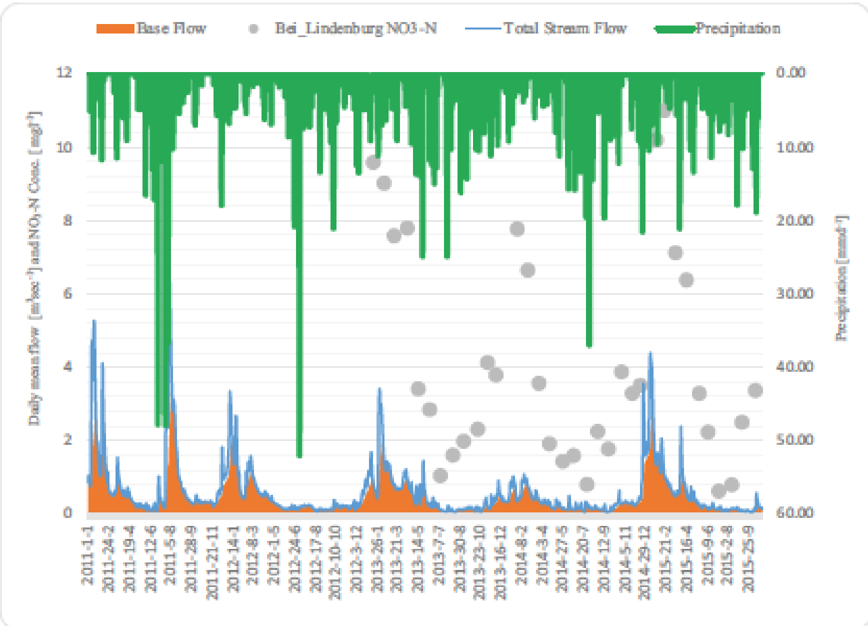


Figure 2.13 Overall trend of SW flow and concentrations in Augraben River catchment

2.5. **Conclusion**

Based on analysis of data collected from monitoring programs indicates that GW is one of the dominant contributor to SW contamination in Augraben River catchment. Test catchment analysis found a strong relationship between SW and GW quality. This means that GW improvement will result in improved standards of SW quality. Different other methods like flow difference method, tracer method etc., need to be considered in combination with gradient flow and flow hydrograph separation method as these are the simplest ways to quantify the GW role in total nitrogen loads in surface waters by just using the available monitoring data. For a better local resolution and process understanding, it would be beneficial to perform flow monitoring at the outlets of drainage channels small channels entering into the Augraben. It is also advisable to collect the GW concentration data in higher resolution than on a seasonal basis. This way, the correlation between land use and GW concentrations can be described more reliably by combining the data analysis and simple flow equations. Regarding the EU nitrate directive and EU WFD, the NO_3-N concentration in GW are twice over the limit at Au II Alt Kentzlin and requires maximum efforts to reduce NO_3-N pollution in the study area.

Software Availability

BFI+3.0 can be downloaded from the following link and it is open to use.

https://hydrooffice.org/Downloads?Items=Software

References

[1] Novotny V, Chesters G. Handbook of nonpoint pollution: sources and management. New York: Van Nostrand-Reinhold; 1981.

[2] Ritter WF, Shirmohammadi A, editors. Agricultural nonpoint source pollution. Boca Raton London New York Washington DC: Lewis; 2001.

[3] Heathwaite, L., Sharpley, A., & Gburek, W. (2000). A conceptual approach for integrating phosphorus and nitrogen management at watershed scales. Journal of Environmental Quality, 29(1), 158-166.

[4] Spalding RF, Exner ME. Occurrence of nitrate in GW—a review. J Environ Qual 1993; 22:392–402.

[5] Campling, P., Terres, J.M., Vande Walle, S., Van Orshoven, J., Crouzet, P., 2005. Estimation of nitrogen balances from agriculture for EU-15: specialisation of estimates

to River basins using the CORINE Land Cover. Physics and Chemistry of the Earth 30, 25e34.

[6] Nitratbericht 2016 Gemeinsamer Bericht der Bundesministerien für Umwelt, Naturschutz, Bau und Reaktorsicherheit sowie für Ernährung und Landwirtschaft

[7] Randall, D.J.; Tsui, T.K.N., (2002). Ammonia toxicity in fish, Mar. Pollut. Bull., 45(1): 17-23

[8] Haralambous, A.; Maliou, E.; Malamis, M., (1992). The use of zeolite for ammonium uptake, Water Sci. Technol., 25(1): 139145

[9] Ip, Y.K.; Chew, S.F.; Randall, D.J., (2001). Ammonia toxicity, tolerance, and excretion, Fish Physiol., (20): 109-148

[10] Van der Molen, D.T., Breeuwsma, A., Boers, P.C.M., 1998. Agricultural nutrient losses to surface water in the Netherlands: impact, strategies, and perspectives. Journal of Environmental Quality 27 (1), 4e11.

[11] Oenema, O., Roest, C.W.J., 1998. Nitrogen and phosphorus losses from agriculture into surface waters; the effects of policies and measures in the Netherlands. Water Science and Technology 37 (3), 19e30.

[12] Oenema, O., Van Liere, L., Schoumans, O., 2005. Effects of lowering nitrogen and phosphorus surpluses in agriculture on the quality of GW and surface water in the Netherlands. Journal of Hydrology 304 (1e4), 289e301.

[13] Addiscott TM, Wagenet RJ. Concepts of solute leaching in soils: a review of modelling approaches. J Soil Sci 1985;36:411–24.

[14] HELCOM 2010a. Ecosystem Health of the Baltic Sea - HELCOM Initial Holistic Assessment. Baltic Sea Environment Proceedings 122. 63 pp.

[15] HELCOM, 2007. Baltic Sea action plan. In: HELCOM Ministerial Meeting. Krakow, Poland. pp. 101. HELCOM, 2011.

[16] Fifth Baltic Sea pollution load compilation (PLC-5) balt. Sea Environ. Proc. No. 128. HELCOM, 2013. Taking Further Action to Implement the Baltic Sea Action Plan – Reaching Good Environmental Status for a Healthy Baltic Sea. HELCOM pp. 19 Copenhagen, Denmark. (Accessed 3 October 2013).

[17] Updated Fifth Baltic Sea pollution load compilation (PLC-5.5). Retrieved fromhttp://www.helcom.fi/Lists/Publications/BSEP145_Lowres.pdf

[18] Saaltink, R., van der Velde Ype Dekker, S.C., Lyon, S.W., Dahlke, H.E., 2014. Societal: land cover and climatic controls on river nutrient flows into the Baltic Sea. J. Hydrol.: Reg. Stud. 1, 44–56.

[19] Hinsby, K., Markager, S., Kronvang, B., Windolf, J., Sonnenborg, T. O., & Thorling, L. (2012). Threshold values and management options for nutrients in a catchment of a temperate estuary with poor ecological status. Hydrology and Earth System Sciences, 16(8), 2663-2683.

[20] Wendland F., Keller L., Kuhr P., Kunkel R., Tetzlaff B. (2015) Regional differenzierte Quantifizierung der Nährstoffeinträge in das Grundwasser und in die Oberflächengewässer Mecklenburg-Vorpommerns unter Anwendung der Modellkombination GROWADENUZ-WEKU-MEPhos, Endbericht, Herausgeber: LUNG Güstrow.

[21] Brook Zarnow gauging station Zarnow basin, Germany. Retrieved from http://ne-friend.bafg.de/servlet/is/17796/Zarnow.pdf

[22] Koch F (2014) Diffuse Nährstoffbelastungen in Oberflächengewässern und im Grundwasser, 19. Gewässersymposium, 19.11.2014 Güstrow.

[23] Rostock. Meeresbiolog. Beitr (2004). Nährstoffausträge in die Ostsee aus diffusen Quellen Mecklenburg-Vorpommerns und Schleswig-Holsteins Nutrient emissions from diffuse sources of Mecklenburg-West Pomerania and Schleswig-Holstein to the Baltic Sea.

[24] McLay CDA, Dragten R, Sparling G, Selvarajah N. Predicting GW nitrate concentrations in a region of mixed agricultural land use: a comparison of three approaches. Environ Pollut 2001;115:191–204.

[25] Methods for estimating GW discharge to streams – summary of field trials.

[26] Rapid Eye Science Archive (RESA). Retrieved from (resa.blackbridge.com)

[27] Nikkarinen, M., Kauniskangas, E. and Nenonen, K.: 1996, Use of geological and geochemical data for the derivation of maps for environmental planning in Iisalmi, Finland, Applied Geochemistry, 11, 261–270.

[28] Canter, L.W., Knox, R.C. and Fairchild, D.M.: 1988, Ground Water Quality Protection. Lewis Publishers, Chelsea, 562p

[29] Lee, S.H. and Kim, Y. L.: 1996, The management of GW contamination in Seoul using GIS, Proceedings of Journal of the Korean society of GW environment, 40–44

[30] ESRI: 1994, Understanding GIS. ESRI, Inc., Redlands, pp. 2–31

[31] BIOTA (2012): Überarbeitung und Aktualisierung der Karte der mittleren Abflüsse und mittleren Niedrigwasserabflüsse für Mecklenburg-Vorpommern. - biota - Institut für ökologische Forschung und Planung GmbH im Auftrag des Landesamtes für Umwelt, Naturschutz und Geologie Mecklenburg-Vorpommern, 97 S.

[32] Tallaksen, L. M., & Van Lanen, H. A. (Eds.). (2004). Hydrological drought: processes and estimation methods for streamflow and GW (Vol. 48). Elsevier.

[33] Sloto, R. A., & Crouse, M. Y. (1996). HYSEP, a computer program for streamflow hydrograph separation and analysis. US Department of the Interior, US Geological Survey.

[34] HALL, F., R., 1968: Base flow recessions – a review. Water Resources Research 4(5), 973-983

[35] Arnold, J. G., and N. Fohrer. 2005. SWAT2000: Current capabilities and research opportunities in applied watershed modelling. Hydrol. Proc. 19(3): 563-572.

[36] LYNE, V., HOLLICK, M., 1979: Stochastic time-variable rainfall-runoff modelling. Institute of Engineers Australia National Conference. Pub. 79/10, 89-93.

[37] Gregor, M. (2010). BFI+ 3.0.

[38] NATHAN, R., J., McMAHON, T., A., 1990: Evaluation of automated techniques for base flow and recession analyses. Water Resources Research 26(7), 1465-1473

[39] Welderufael WA, Le Roux PAL, Hensley M (2009). Quantifying rainfallrunoff relationships on the Melkassa Hypo Calcic Regosol ecotope in Ethiopia. Water SA, 35(5):639-648.

[40] Growing season in Germany. Retrieved from (https://en.wikipedia.org/wiki/Growing_season)

[41] WHO (1985a) Guidelines for the study of dietary intake of chemical contaminants. Geneva, World Health Organization (WHO Offset Publication No. 87).

[42] WHO (1985b) Health hazards from nitrate in drinking-water. Report on a WHO meeting, Copenhagen, 5–9 March 1984. Copenhagen, WHO Regional Office for Europe (Environmental Health Series No. 1).

[43] OGewV 2015, Verordnung zum Schutz der Oberflächengewässer (Oberflächengewässerverordnung-OGewV). Retrieved from https://www.gesetze-im-internet.de/ogewv_2016/BJNR137310016.html

3. Selection of a Suitable Modelling Tool

Based on the research article:

Waseem, M., Kachholz, F., & **Traenckner, J.** (2018). Suitability of common models to estimate hydrology and diffuse water pollution in North-eastern German lowland catchments with intensive agricultural land use. Frontiers of Agricultural Science and Engineering, 5(4), 420-431.

https://doi.org/10.15302/J-FASE-2018243

Abstract: Various process-based models are extensively being used to analyze and forecast catchment hydrology and water quality. However, it is always important to select the appropriate hydrological and water quality modelling tools to predict and analyze the watershed and also consider their strengths and weaknesses. Different factors such as data availability, hydrological, hydraulic, and water quality processes and their desired level of complexity are crucial for selecting a plausible modelling tool. This review is focused on a suitable model selection with a focus on desired hydrological, hydraulic and water quality processes (nitrogen fate and transport in surface, subsurface and groundwater bodies) by keeping in view the typical lowland catchments with intensive agricultural land use, higher groundwater tables, and decreased retention times due to the provision of artificial drainage. In this study, four different physically based, partially and fully distributed integrated water modelling tools, SWAT (Soil and Water Assessment Tool), SWIM (Soil and Water Integrated Model), HSPF (Hydrological Simulation Program– FORTRAN) and a combination of tools from DHI (MIKE SHE coupled with MIKE 11 and ECO Lab), have been reviewed particularly for the Tollense River catchment located in Northeastern Germany. DHI combined tools and SWAT were more suitable for simulating the desired hydrological processes, but in the case of river hydraulics and water quality, the DHI family of tools has an edge due to their integrated coupling between MIKE SHE, MIKE 11 & ECO Lab. In the case of SWAT, it needs to be coupled with another tool to model the hydraulics in the Tollense River as SWAT does not include backwater effects and provision of control structures. However, both SWAT and DHI tools are more data demanding in comparison to SWIM and HSPF. For studying nitrogen fate and transport in unsaturated, saturated, and river zone, HSPF was a better model to simulate the desired nitrogen transformation and transport processes. However, for nitrogen dynamics and transformations in shallow streams, ECO Lab had an edge due

to its flexibility for the inclusion of user-desired water quality parameters and processes. In the case of SWIM, most of the input data and governing equations are similar to SWAT, but it does not include water bodies (ponds and lakes), wetlands, and drainage systems. In this review, only the processes that were needed to simulate the Tollense River catchment were considered. However, the resulted model selection criteria can be generalized to other lowland catchments with similar complexity.

3.1. Introduction

Water resources management requires constant monitoring of water quality and quantity. Proper assessment and management of watershed is the basis for conservation and rational utilization. Environmental policy decisions and successful management execution need robust methods for assessing the hydrology and contribution of point and diffuse pollution sources to water quality problems, and also for assessing the estimated and achieved compliance with the desired watershed hydrology and water quality management objectives [1-3]. Surface, subsurface and groundwater quality is controlled by different key factors such as land use, water management, and agricultural practices, diffuse and point emission sources, lithology, and geological structures of the aquifer [4-7]. Agriculture is the most prominent sector to affect the surface and subsurface water quality acting as a significant diffuse water pollution source through the use of excessive amounts of fertilizers [8-10]. EU Water Framework Directive (WFD) aims to maintain a good ecological status in surface and groundwater bodies, and to prevent any further deterioration in the existing status of waters through hydrological and water quality management practices [11, 12].

In Europe, agricultural diffuse water pollution is responsible for 50% to 80% of the total nitrogen load in surface water systems [13, 14]. Use of fertilizer for agricultural production enhancement continues to negatively affect the overall water quality in Germany and especially in the lowlands due to their higher vulnerability to environmental pollution [15]. Lowlands are comparatively more exposed to environmental and socioeconomic hazards being an epicenter for agricultural production and related agricultural economic activities. In addition, the lack of topography increases their susceptibility to flooding, climate change, and deterioration of water quality resulting from low flow velocities and higher groundwater tables. Soil types in lowland catchments are usually organic soils, e.g., peatlands, bogs, and fens. Due to high groundwater tables, lowland catchments are usually heavily regulated with the provision of drainage systems that result in eutrophication in rivers and lakes due to the reduction in water and nutrient retention times [16]. Decreased retention times means that the fertilizer applied to the crops/plants does not have sufficient time to be taken up by the plants or to decompose through denitrification, resulting in groundwater quality deterioration. Groundwater base flow, and more importantly, the drainage flow increases the nutrient concentrations in surface water bodies and causes higher algae growth and low oxygen levels in surface waters [17-19]. Tollense River has been taken as a representative of northeastern German lowland catchments with all the hydrological, hydraulic and water quality processes in terms of diffuse nitrogen pollution in addition to particular lowland catchment characteristics such as backwater effect, control structures, pump flows, eutrophication, decreased retention times due to provision of drainage, high groundwater and higher inter and base flows.

3.1.1. Tollense river catchment and water quality analysis

The Tollense River is about 30 km long from its source, Tollense Lake, to its confluence with the Peene River at Demmin. Nutrient levels in the river and its tributaries are a concern for achieving a good chemical and ecological status. Within the framework of an ongoing German Government funded project (BOOT-Monitoring, boat-based monitoring of water quality in the Tollense River), water quality is measured continually along a longitudinal section of the Tollense River from Klempenow to Demmin, with an approximate contributing catchment of about 300 km^2 (**Figure 3.1**). The catchment is mainly used for agriculture and is equipped with artificial drainage established during the 60s and 70s. The current land use was estimated by the aerospace images obtained from the Rapid Eye Science Archive website. The study area consists of 2% water, 2% settlements, 18% forest, 75% arable land and pasture, and 3% miscellaneous. The initial results of the boat monitoring project have found nutrient concentrations higher than the permissible water quality limits according to the EU framework directive. A strong correlation between base flow (saturated flow and drainage flow) and the Tollense River nutrient concentrations is observed. The inflow of small water channels mainly fed by inter or drainage flow causes high nutrient concentrations in particular sections of the river. In order to understand the land-use impacts and the fate and transport of nitrogen in the saturated, unsaturated, and river zones, complete integrated hydrological and water quality modelling is necessary.

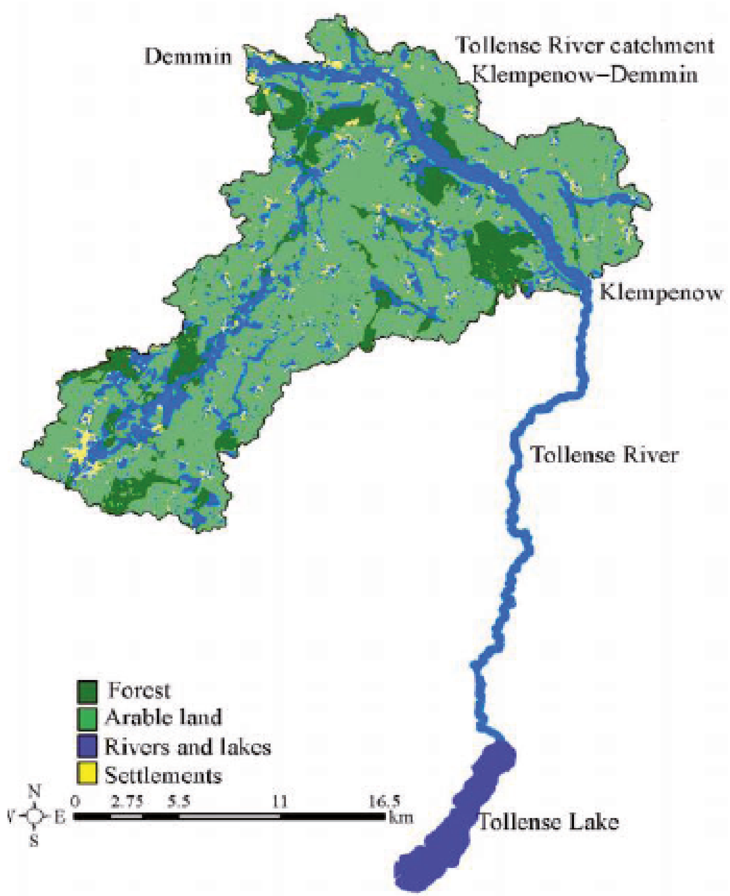


Figure 3.1 Tollense area of investigation (Tollense River catchment from Klempenow to Demmin). Source: Rivers, lakes, and land use data was kindly provided by LUNG-MV (Landesamt für Umwelt, Naturschutz und Geologie Mecklenburg Vorpommern).

To quantify the inflow of nutrients, Gehmkow Augraben, a characteristic tributary of the Tollense River, was studied based on available monitoring data [20]. 25% to 45% of the nutrient content in the Gehmkow Augraben derives from the base flow. Being heavily regulated, artificial drainage is a significant contributor to the higher surface water nutrient concentrations due to decreased retention times. As a result, complete hydrological and water quality modelling is necessary to analyze and predict the hydrology and water quality in the whole Tollense River catchment. The current review study was conducted to find a suitable modelling tool to detect the sources of nutrient pollution and nitrogen dynamics in the Tollense River. Furthermore, it is necessary to quantify the land use impacts on the nutrients concentrations in the groundwater and then via groundwater and drainage flow in the Tollense River, as the available mass balances are insufficient to understand the dynamics and transport patterns of nutrients through surface and subsurface sources. **Figure 3.2** shows the overall water quality and nutrient concentrations in Gehmkow Augraben at the Lindenburg flow and surface water quality monitoring station.

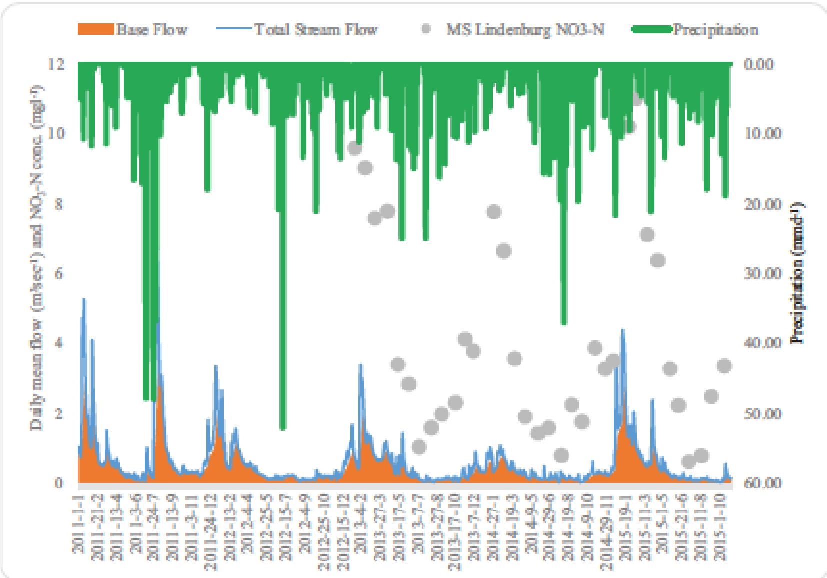


Figure 3.2 Relationship between precipitation, measured surface and estimated base flow with NO_3-N concentrations in Gehmkow Augraben at surface water quality monitoring station (MS) Lindenburg [20].

To determine the water quality in the Tollense River catchment, a measurement program was conducted from January to December 2017 to measure the groundwater concentrations of nitrate, nitrite, and ammonium. 20% of the sampling stations showed higher NO_3-N concentration than the recommended limits of EU WFD. The collected data will be used for calibrating the modelling results, but it also raises the need for an integrated hydrological and water quality modelling in the area to determine the causes of higher nutrient concentrations in the groundwater. This review study focused mainly on the selection of an appropriate modelling tool to quantify the hydrology and water quality in lowland catchments and explains and compares different widely used integrated water modelling tools, their intended use, parameters and processes, limitations, strengths and their application to particular conditions. The selected models (described below) differ greatly in the degree of complexity in explaining the catchment spatially, temporally and also the complexity of their representation of the physical, chemical, and biochemical processes involved in forecasting the fate and transport of nutrients in surface and subsurface waters. This report will allow researchers to make informed decisions when selecting a suitable model to predict hydrology and water quality in lowland catchments.

3.1.2. Brief description of models

Here the following four physically based, distributed modelling tools are briefly explained according to their advantages and disadvantages, and their ability to simulate the shallow rivers.

3.1.2.1. Hydrological simulation program–FORTRAN (HSPF)

HSPF is a semi-distributed, constant simulation model developed by HYDROCOMP, Inc. under a contract from the US Environmental Protection Agency in 1980 and until now the model was considered as one of the best simulating tools to model comprehensively watershed and water quality with a comparatively high level of flexibility [21-23]. HSPF can represent contributions of nutrients, sediment, pesticides, conservatives and faecal coliforms from agricultural areas and to continually simulate and predict water quality in pervious and impervious land surfaces, streams and well-mixed impoundments [21, 24-25]. It is capable of simulating the water quality processes in a watershed by taking into account both diffuse and point sources of pollution [26, 27].

3.1.2.2. Soil and water assessment tool (SWAT)

SWAT developed by the US Department of Agriculture, is a continuous in time, physically based, distributed water quality model for the prediction of long-term effects of rural and agricultural practices on water quality in large composite watersheds with variable soils, land use and management practices [28, 29]. SWAT is proficient in modelling a single catchment or a system of hydrologically connected subcatchments. The GIS based interface model, ArcSWAT, defines the river network and the point of catchment outflow, and the distribution of subcatchments and hydrological response units (HRU). HRUs comprise parts of each subcatchment with a distinctive mixture of land use, soil, topography and land management practices. This helps SWAT to model various parameters, including ET, erosion, plant growth, surface flow, and water balance for each subcatchment or HRU, which increases the precision of the simulation results [30]. SWAT daily water balance takes into account actual evapotranspiration, plant transpiration, canopy interception, surface runoff, soil evaporation, and vertical water movement in the unsaturated soil zone to the aquifer [31]. For nitrogen transformation and transport, SWAT takes into account both point and diffuse sources of emissions (fertilizer applications as diffuse sources and outflow from wastewater treatment plants as point sources in the case of the Tollense River catchment) [32, 33]. SWAT simulates the nitrogen cycle and losses to the river network in various forms (dissolved and particulate) through surface runoff, sediment, tile drainage, and aquifer [31].

3.1.2.3. Soil and water integrated model (SWIM)

SWIM is a time-continuous, spatially semi-distributed model with an ability to simulate integrated hydrological processes, nutrient cycle, vegetation growth, and sediment transport at the catchment scale. The system also includes the interface to the geographic information system GRASS (Geographic Resources Analysis Support System) [34], which provides the freedom to extract spatially distributed parameters of land use, soil, elevation, hydrotope and routing structure for the basin under consideration [35]. Model objectives include a comprehensive GIS-based tool for the coupled hydrological and water quality simulation in large scale watersheds ranging from 100 to 10,000 km2. Climate change and land use impacts on hydrological processes, agricultural food production, and water quality deterioration at a regional scale can be simulated and analyzed with SWIM [36].

3.1.2.4. DHI tools (MIKE SHE, MIKE 11, and ECO Lab)

MIKE SHE [37] is a physically-based, fully distributed modelling system capable of analyzing all significant processes in the land phase of the hydrologic cycle. MIKE SHE simulates all the processes in the hydrological cycle by fully integrating the surface, subsurface, and groundwater flow [38-40]. MIKE 11 is a hydraulic river model capable of simulating potential hydrology and flood risks. Moving from hydraulic model to water quality model, the upper boundary simulates water temperatures by allowing heat balance and wind options within the hydrodynamic module. This allows the use of comprehensive heat calculations, which consider humidity, air temperature, sunshine hours, and wind speed to model and predict water temperatures alongside the river. The advection-dispersion module determines the movement of water quality in the system through advection and dispersion processes. The ECO Lab water quality module simulates the biogeochemical cycling of water quality factors. ECO Lab module contains several standard templates, comprising different combinations of water quality determinants and processes, including water temperature, salinity, dissolved oxygen, biochemical oxygen demand, ammonia, nitrate, and orthophosphate. Overall, ECO Lab needs a large amount of data, and it is difficult to simulate the determinants without having a sufficient amount of data [41].

3.2. Materials and Methods

This study focused on the selection of a suitable modelling tool. The model selection framework is based on (1) desired hydrological and hydraulic processes, (2) specific characteristics of hydrological and water quality models (governing equations, and spatial and temporal resolution, (3) data availability, (4) ability to model the fate and transport of nitrogen in surface, subsurface and saturated water zones.

3.2.1. Hydrological and hydraulic processes

Desired hydrological and hydraulic processes simulated by a model are the key arguments to determine whether the model has the ability to predict the required results. Desired hydrological processes in the case of the Tollense River catchment require precipitation, interception, evapotranspiration, infiltration, and transport of nutrients through surface and subsurface flow. In the case of hydraulics, the Tollense River has a problem of backwater effects from the Peene River in the periods with low flow in the Tollense. The Tollense River is equipped with three broad-crested weirs with gates, so it also needs a control strategy to operate the gates in periods of high and low flows. All the models included in this study are physically-based distributed models and can simulate the watershed. **Figure 3.3** and **Table 3.1** explains the desired hydrological and hydraulic processes and the ability of different selected models to simulate the desired processes in a lowland catchment.

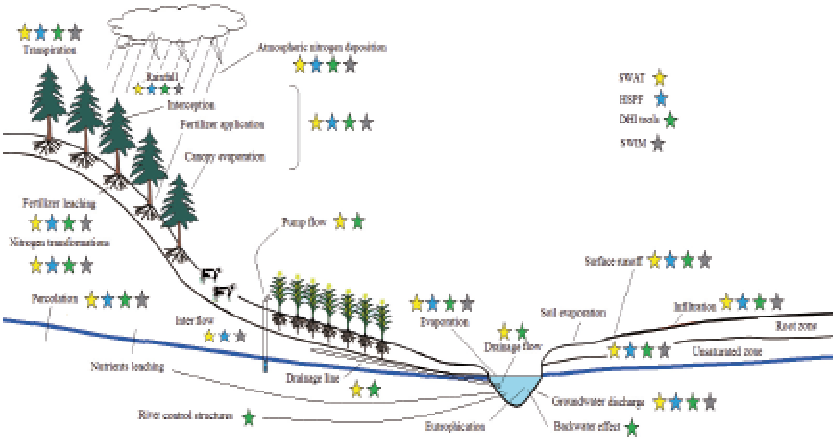


Figure 3.3 Desired hydrological and hydraulic processes in the study area of the Tollense River catchment.

Table 3.1 Ability to model the desired hydrological processes by selected modelling tools.

Desired hydrological processes	**Relevant models**			
	SWAT	HSPF	MIKE SHE	SWIM
Surface runoff	•	•	•	•
Evapotranspiration	•	•	•	•
Infiltration	•	•	•	•
Interflow	•	•		•
Base flow	•	•	•	•
Pumping flow	•		•	
Drainage	•		•	
Urban drainage	•		•	

The channel flow calculation can be realized by coupling the hydrological model to a hydrodynamic model. The reason why hydrological models are not used for simulating open channel flow is that their use of simple flow routing methods, which concentrate only on flood wave delays and attenuation such as the linear reservoir model [42] and Muskingum method [43]. That means the desired hydraulic processes, such as backwater effect, operation of control structures, and pump operations cannot be taken into account. 1D hydraulic models simplify the river channel into a number of cross-sections perpendicular to the channel centerline, and the floodplain is viewed as an extended cross-section. These models can provide a good explanation of flood routing for in-bank flows and are extensively in practice. Examples of well-known 1D hydraulic modelling systems include ISIS [44], MIKE 11[45] , and HEC-RAS [46]. Due to simplification, 1D models are incapable of precisely reproducing floodplain inundations and flows over complex topography. 3D hydraulic models, such as FLUENT [47] and MIKE 3 [48], involve full representations of flow processes in three-dimensions. These models may potentially provide an improved representation of the physical flow processes and hence more precise results, but they are also computationally challenging due to the complex model structures. Unlike hydraulic models based on kinematic wave equations, hydraulic models using diffusive, dynamic, or inertial wave equations can handle backwater effects. These models can be coupled with defined hydrological models but will require data preparation tools to modify the hydrological model's output accordingly. The internal coupling has also been reported in the literature [49], and the governing equations for hydraulic models and hydrological models can be solved separately, with information at the shared boundaries updated and exchanged at each computational time step [50].

3.2.2. Specific characteristics of hydrological and water quality models

Governing equations, spatial and temporal resolutions are elementary to all the hydrologic models and affect the performance and applicability of a model. In physically-based models, mass transfer, momentum, and energy are analyzed usually by using Saint-Venant equations for surface flow, Richards equation for unsaturated flow, an empirical Kristensen and Jensen method for evapotranspiration and Darcy equation for groundwater flow calculations and are solved by various numerical methods. Saint-Venant equations or dynamic wave equations consist of continuity and momentum for gradually varied unsteady flow, require much computing time, and are not often used in catchment modelling. Diffusive and kinematic wave equations are used in many surface runoff routing models. In diffusive wave equations, continuity equations and momentum equations ignoring dynamic terms (local and convective accelerations) are used while in kinematic wave equations, the momentum equation is approximated by ignoring all the acceleration and pressure gradient terms of the dynamic momentum equation (i.e., energy gradient is equal to bed slope). DHI tool (MIKE SHE) uses diffusive wave equations and finite difference approximation for their solutions. SWAT uses the Soil Conservation Service runoff curve number method to compute runoff volumes and other empirical relations to compute peak flows [38, 51]. The transfer of parameter sets over different temporal and spatial resolutions is usual practice in many large-scale modelling hydrological studies. The amount to which parameters are transferable across temporal and spatial resolutions is also a key factor for understanding how well spatial and temporal variability is simulated in the models [52]. **Table 3.2** shows the strength of models based on their resolution (spatial and temporal) and applied governing equations.

Table 3.2 Governing equations, spatial and temporal resolution of selected modelling tools

Resolution	Governing equation
SWAT **Spatial: flexible,** **Temporal:** **continuous [38, 54]**	• Runoff volume (Modified SCS-curve number or G&A infiltration method) • Peak runoff rate (modified rational formula or the SCS TR-55 method) • Lateral subsurface flow & percolation (kinematic storage routine) [53] • Potential evapotranspiration (Hargreaves, Priestley-Taylor and Penman-Monteith equations) • Sediment yield (modified universal soil loss equation) • Water routing (variable storage coefficient method or Muskingum routing method and Manning's equation to define flow)
HSPF **Spatial: flexible,** **Temporal: flexible or user-defined time step [54]**	• HSPF uses basic continuity to model water flow through the channel [55] (otherwise known as storage routing or kinematic wave).
	• Surface runoff volume (modified SCS-curve number technique)

SWIM **Spatial: flexible,** **Temporal: daily [56]**	• Peak runoff rate (modified rational formula) • Storage routing technique [57] • Lateral subsurface flow kinematic storage routine [53] • Potential evapotranspiration [58] • Soil evaporation and plant transpiration [59] • Groundwater flow [60] • Transmission losses [61]
MIKE SHE **Spatial: flexible,** **Temporal: event based &continuous [38]**	• Runoff on overland (2D diffusive wave equations) • Runoff in channels (1D diffusive wave equations solved by implicit fine-difference method) • Vertical flow (Richards equations) • Actual evapotranspiration [62] • Subsurface flow (3D groundwater flow equations solved using numerical finite-difference method and simulated river ground water exchange) • Chemical simulations (numerically solved advection-dispersion equation)

3.2.3. Input data requirement

Input data required to run a model is another important criterion for the selection and application of any hydrologic and water quality model. Lack of required data is a major constraint, especially in the developing world, for the successful application of a model. The MIKE SHE and the SWAT model require extensive data but can be managed with readily available datasets from various public sources, as in case of the Tollense, most of the hydrological and water quality data was provided by LUNG-MV (Landesamt für Umwelt, Naturschutz und Geologie Mecklenburg Vorpommern) and StÄLU (Staatliche Ämter für Landwirtschaft und Umwelt Mecklenburg Vorpommern). Climate data was collected from DWD (Deutsche Wetterdienst), German Weather Services Department. On average, MIKE SHE and SWAT have extensive input data requirements, while HSPF and SWIM require least input data to run the model shown in **Table 3.3**.

Table 3.3 Input data required by the selected hydrological and water quality models [22, 23, 37, 38, 53-55, 63-67]

Tool	Category	Parameters

SWAT	Climate (6)	Rainfall, air temperature, solar radiation, wind speed, evapotranspiration, and humidity/dew point
	Hydrology and hydrogeology (7)	Water table height, hydraulic conductivity, groundwater extraction, initial shallow aquifer storage, recharge water, drain spacing, and irrigation
	Soil data (7)	Layer thickness, bulk density, initial soil water content, field capacity*, wilting point*, hydraulic conductivity, and porosity
	Land use and vegetation (7)	Land use, vegetation type, vegetation height, leaf area index, root depth, fertilizing rate, and crop management
	Topography (6)	Area, elevation, land surface slope length, land surface slope steepness, hill slope length, and hillslope steepness
MIKE SHE	Climate (5)	Rainfall, air temperature, solar radiation, wind speed, and grass reference evaporation
	Hydrology and hydrogeology (9)	Water table height, hydraulic conductivity (x-, y- and z-directions), specific yield, specific storage, groundwater extraction, initial shallow aquifer storage, recharge water, drain spacing, and irrigation
	Soil data (6)	Layer thickness, bulk density, initial soil water content, field capacity, wilting point, and hydraulic conductivity
	Land use and vegetation (5)	Land use, vegetation type, leaf area index, root depth, and fertilizer application rates
	Topography (1)	Digital elevation model
HSPF	Climate (6)	Rainfall, air temperature, solar radiation, wind speed, evapotranspiration, and humidity/dew point
	Hydrology and hydrogeology (3)	Active groundwater storage, interflow storage, and lower zone storage

	Soil data (3)	Layer thickness, bulk density, and initial soil water content
	Land use and vegetation (2)	Land use, and vegetation type
	Topography (4)	Area, elevation, land surface slope length, land surface slope steepness
SWIM	Climate (6)	Rainfall, air temperature, solar radiation, wind speed, evapotranspiration, and humidity/dew point
	Hydrology and hydrogeology (6)	Water table height, hydraulic conductivity, specific yield, groundwater extraction, drain spacing, Irrigation
	Soil data (7)	Layer thickness, bulk density, initial soil water content, field capacity, wilting point, hydraulic conductivity, and porosity
	Land use and vegetation (5)	Land use, vegetation type, leaf area index, root depth, and fertilizer application rates
	Topography (7)	Area, elevation, land surface slope length, land surface slope steepness, hill slope length, hill slope steepness, and hillslope width

*Provided as input or calculated by the model.

3.2.4. Nitrogen dynamics

For the simulation of nutrient fate, additional input data are required to characterize the system. The major forms of N inputs described in models are organic N, fresh organic N, active organic N, dissolved N, NO_3^-, NO_2^-, NH_4^+, NH_3, and total N. The sources of N inputs shown in **Table 3.4** are mainly soil, groundwater, surface water bodies, plant uptake, urban source, point source, fertilizer, and atmosphere.

Table 3.4 Input required for predicting nitrogen transformations and transport in surface and subsurface water [39, 53-55, 62-67]

Item	Relevant models			
	SWAT	SWIM	ECO Lab*	HSPF
Initial soil nitrogen				

Organic N	•	•	•	•
NO_3^-	•	•	•	•
NH_4^+		•		•
Point sources				
Organic N	•		•	
NO_3^-	•		•	
NO_2^-	•		•	
NH_4^+	•		•	
Fertilizer nitrogen (crop-specific)				
Organic N	•		•	
Active organic N		•	•	
Inorganic N	•		•	
NH_4^+	•		•	
In-stream nitrogen				
Organic N	•		•	
NO_3^-	•		•	•
NO_2^-	•		•	•
NH_4^+	•		•	
Atmospheric deposition				
NO_3^- in rain	•	•		
NH_4^+ in rain	•			

*ECO Lab is not a model, but a module that works in combination with MIKE SHE and MIKE 11 model to simulate the nitrogen fate and transport in groundwater and surface water.

3.3. Results and Discussion

It is expected that the simpler the model, the more imprecise the understanding. Therefore, basic models could be used for the initial characterization of a surface water body. As more reliable data are available, a more refined and improved model could be used. Therefore, during the selection of the model the key issue is the availability of data for the key parameters in time and space. However, it should also be acknowledged that more complicated models do not necessarily result in more accurate understanding of the processes being described. A prudent approach is to start with a basic model and gradually move to more detailed and comprehensive model. Data requirement is usually an important aspect of selecting a model. All four models have the tendency to model the catchment on average, but in terms of hydrological processes SWAT and MIKE SHE demand more data in comparison to HSPF and SWIM, but at the same time can take into account all the desired hydrological processes including pump flow and drainage, not included by HSPF and SWIM. In case of topography in MIKE SHE, the parameters needed are less than the other models because it takes a digital elevation model as an input to simulate the topography, while in case of SWIM, the higher number of topographical input parameters needed makes it more data demanding. In case of SWIM, most of the input data and governing equations are similar to SWAT but it does not include water bodies (ponds and lakes), wetlands and drainage system. In terms of hydraulic processes, none of the selected hydrological models have the ability to simulate the hydraulic processes involved in the Tollense River basin. All these models need to be coupled with another model to analyze and predict the backwater effect and control strategy for operation of weirs and gates. Here MIKE SHE is considered good, being a component of the DHI software family, as it can be coupled with MIKE 11, which can simulate backwater effect, pump flows, river gates, and weir operations. **Figure 3.4** shows the input data requirements of the models.

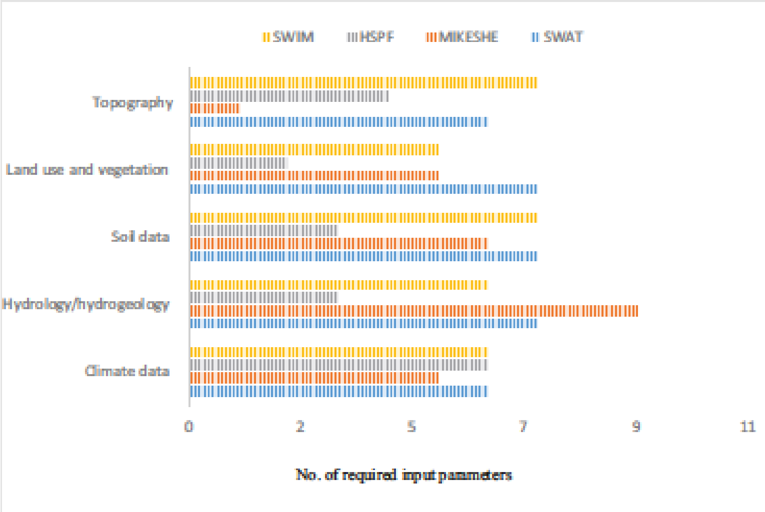


Figure 3.4 Summary of minimum input parameters required by the selected models.

For N transport and transformations, ECO Lab and HSPF are better and include the N cycle in comparison to SWIM and SWAT. A problem in using SWAT for nitrogen transformation is the use of only built-in parameters, and new parameters cannot be included. MIKE SHE has a shell or module called ECO Lab, which has the tendency to model the nitrogen transformations in the river and desired parameters can be added accordingly. SWAT and SWIM do not have the ability to simulate the soil nitrogen and in terms of interflow which is a considerable part in the case of the Tollense River basin. SWAT and SWIM can only model NO_3^-, while ECO Lab and HSPF can predict both NO_3^- and NH_4^+ in interflow. Interflow inorganic N, however, can only be simulated with ECO Lab. The case of groundwater flow follows the same pattern, with SWIM and SWAT only predicting NO_3^-, while ECO Lab can predict NO_3^-, NH_4^+ and dissolved N, whereas HSPF can only predict the first two. Nitrification, denitrification and decomposition can be handled by all tools. For plant uptake, SWAT and SWIM can only simulate inorganic N taken up by plants, whereas, HSPF cannot model inorganic N but can model NO_3^-, NH_4^+, and ECO Lab can handle all three parameters. These differences are summarized in **Table 3.5**.

Table 3.5 Prediction of nitrogen transformations and transport in surface and subsurface waters by the selected models [59-62]

Item	**Relevant models**			
	SWAT	SWIM	ECO Lab	HSPF
Soil nitrogen				
Organic N			•	•
NO_3^-			•	•
NH_4^+			•	•
Transport through surface runoff				
NO_3^- in water	•	•	•	•
NH_4^+ in water			•	•
Transport through interflow				
NO_3^-	•	•	•	•
NH_4^+			•	•
Inorganic N			•	
Transport through subsurface drainage flow				
Inorganic N			•	
Transport through groundwater flow				
NO_3^-	•		•	•
NH_4^+			•	•
Transformation				
Fixation	•		•	
Nitrification	•		•	•
Ammonia volatilization	•		•	•
Denitrification	•	SWIM	•	•
Adsorption and desorption				
Total N	•			•

Model openness, availability of graphical user interface, and online support are other important considerations in selecting the appropriate model and also depend on the available budget for a particular study. **Table 3.6** details these aspects of the models and their origins with their license requirements.

Table 3.6 Openness, availability of graphical user interface and online support for selected models [53-67]

Item	Model type	Flexibility to grid structure	Flexibility in resolution	Possibility of calibration
SWAT	Physically based and distributed	sub-basin structure but can be operated on grids	depends on the definition of sub-basins	automatic and manual
HSPF	Physically based and distributed	sub-basin structure but can be operated on grids	depends on the definition of sub-basins	tools available
SWIM	Physically based and semi-distributed	sub-basin structure but can be operated on grids	depends on the definition of sub-basins and hydrotopes	tools available
DHI tools	Physically based and distributed	flexible	flexible	automatic and manual
Tools availability	• SWAT: https://swat.tamu.edu • HSPF: https://www.epa.gov/ceam / hydrological-simulation-program-FORTRAN-HSPF • SWIM: Potsdam Institute for Climate Impact Research, Potsdam, Germany • DHI Tools: https://www.mikepoweredbydhi.com			
License agreement	• SWAT: open source • HSPF: open • SWIM: provided on request • DHI tools: license required			

3.4. Conclusion

The models were designed and verified for a specific area and were built around the data currently available to the developers, so different hydrological conditions and unavailability of the required input data will limit the use of specific modelling tools. In addition, for more complex models, the data requirements are often so high that it is difficult to collect all the required data, especially when the model is to be applied to a large area. This review was focused on the desired objective of modelling the nitrogen dynamics in lowland catchments by considering the hydrological, hydraulic and water quality processes. This study aimed to be objective, and does not declare any judgment about good or bad modelling tools, but rather made comparisons based on multi-criteria analysis. In this review, the Tollense River catchment was considered as a characteristic example of northeastern lowland catchments, and unique lowland catchment characteristics served as a representative for selecting a suitable modelling tool. DHI tools and SWAT are able to model the desired hydrological processes in detail, but in case of hydraulic processes, DHI tools have the edge over SWAT due to their integrated coupling within the DHI tools as SWAT needs coupling with other modelling tools to handle the hydraulic processes. For nitrogen fate and transport in unsaturated, saturated, and river zones, HSPF is a better model to simulate the desired nitrogen transformation and transport processes. In contrast, in the case of nitrogen dynamics and transformations in shallow streams, ECO Lab has an edge due to its openness for the inclusion of user-desired water quality parameters and processes. However, for lowland catchments, where integrated modelling is required to determine the impacts of land use on surface and subsurface water and the nitrogen dynamics in a river, DHI tools are a good compromise. Overall, open-source tools such as SWAT are preferable due to a large number of users, available literature, and platforms for sharing problems and issues. This review focused on northeastern German lowland catchments but can be generalized to the other similar lowland catchments.

References

1. Ziemińska-Stolarska A, Skrzypski J. Review of mathematical models of water quality. *Ecological Chemistry and Engineering S*, 2012, 19(2): 197-211
2. Yang Y S, Wang L. A review of modelling tools for implementation of the EU water framework directive in handling diffuse water pollution. *Water Resources Management*, 2010, 24(9): 1819-1843
3. Arhonditsis G B, Adams-VanHarn B A, Nielsen L, Stow C A, Reckhow K H. Evaluation of the current state of mechanistic aquatic biogeochemical modelling: Citation analysis and future perspectives. *Environmental Science & Technology*, 2006, 40(21): 6547-6554

4. Loukas A. Surface water quantity and quality assessment in Pinios River, Thessaly, Greece. *Desalination*, 2010, 250(1): 266-273

5. Melidis P, Akratos C S, Tsihrintzis V A, Trikilidou E. Characterization of rain and roof drainage water quality in Xanthi, Greece. *Environmental Monitoring and Assessment*, 2007, 127(1-3): 15-27

6. Naseem S, Hamza S, Bashir E. Groundwater geochemistry of Winder agricultural farms, Balochistan, Pakistan and assessment for irrigation water quality. *European Water*, 2010, 31: 21-32

7. Tsakiris G, Alexakis D. Water quality models: an overview. *European Water*, 2012, 37: 33-46

8. Carpenter S R, Caraco N F, Correll D L, Howarth R W, Sharpley A N, Smith V H. Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecological Applications*, 1998, 8(3): 559-568

9. Vörösmarty C J, McIntyre P B, Gessner M O, Dudgeon D, Prusevich A, Green P, ... Davies P M. Global threats to human water security and river biodiversity. *Nature*, 2010, 467(7315): 555

10. EEA (European Environmental Agency). European waters - assessment of status and pressures, EEA Report No 8/2012. *European Environment Agency, Copenhagen*, 2012

11. Heinz I, Pulido-Velazquez M, Lund J R, Andreu J. Hydro-economic modelling in river basin management: implications and applications for the European water framework directive. *Water Resources Management*, 2007, 21(7): 1103-1125

12. Krause S, Jacobs J, Bronstert A. Modelling the impacts of land-use and drainage density on the water balance of a lowland-floodplain landscape in northeast Germany. *Ecological Modelling*, 2007, 200(3-4): 475-492

13. Bøgestrand J, Kristensen P, Kronvang B. Source apportionment of nitrogen and phosphorus inputs into the aquatic environment, 2005

14. Kronvang B, Behrendt H, Andersen H E, Arheimer B, Barr A, Borgvang S A, ... Schwaiger E. Ensemble modelling of nutrient loads and nutrient load partitioning in 17 European catchments. *Journal of Environmental Monitoring*, 2009, 11(3): 572-583

15. Nitratbericht. *Gemeinsamer Bericht der Bundesministerien für Umwelt, Naturschutz, Bau und Reaktorsicherheit sowie für Ernährung und Landwirtschaft*, 2016

16. Trepel M, Palmeri L. Quantifying nitrogen retention in surface flow wetlands for environmental planning at the landscape-scale. *Ecological Engineering*, 2002, 19(2): 127-140

17. Kieckbusch J J, Schrautzer J. Nitrogen and phosphorus dynamics of a re-wetted shallow-flooded peatland. *Science of the Total Environment*, 2007, 380(1-3): 3-12

18. Tiemeyer B, Lennartz B, Kahle P. Analysing nitrate losses from an artificially drained lowland catchment (North-Eastern Germany) with a mixing model. *Agriculture, Ecosystems & Environment*, 2008, 123(1-3): 125-136

19. Krause S, Heathwaite A L, Miller F, Hulme P, Crowe A. Groundwater-dependent wetlands in the UK and Ireland: controls, functioning and assessing the likelihood of damage from human activities. *Water Resources Management*, 2007, 21(12): 2015-2025

20. Waseem M, Koegst T, Tränckner J. Groundwater Contribution to Surface Water Contamination in a North German Low Land Catchment with Intensive Agricultural Land Use. *Journal of Water Resource and Protection*, 2018, 10(03): 231

21. Barnwell T O, Johanson R. HSPF: A comprehensive package for simulation of watershed hydrology and water quality. *Nonpoint Pollution Control– Tools and Techniques for the Future, Proceedings of a Technical Symposium*, 1981, 135-153

22. Munson A D. HSPF modelling of the Charles River Watershed. Doctoral dissertation. *Massachusetts Institute of Technology*, 1998

23. Water Quality Modelling Basics and Beyond. https://www.epa.gov/sites/production/files/201510/documents/flyer_water_quality_models101.pdf, 2018-6-24

24. Crawford N H, Linsley R K. Digital Simulation on Hydrology: Stanford Watershed Model IV. *Stanford University Technical Report No. 39*, 1966

25. Tzoraki O, Nikolaidis N P. A generalized framework for modelling the hydrologic and biogeochemical response of a Mediterranean temporary river basin. *Journal of Hydrology*, 2007, 346(3-4): 112-121

26. Gallagher M, Doherty J. Parameter estimation and uncertainty analysis for a watershed model. *Environmental Modelling & Software*, 2007, 22(7): 1000-1020

27. Ribarova I, Ninov P, Cooper D. Modelling nutrient pollution during a first flood event using HSPF software: Iskar River case study, Bulgaria. *Ecological Modelling*, 2008, 211(1-2): 241-246

28. Srinivasan R, Ramanarayanan T S, Arnold J G, Bednarz S T. Large area hydrologic modelling and assessment part II: model application 1. *JAWRA Journal of the American Water Resources Association*, 1998, 34(1): 91-101

29. Ficklin D L, Luo Y, Zhang M. Watershed modelling of hydrology and water quality in the Sacramento River watershed, California. *Hydrological Processes*, 2013, 27(2): 236-250

30. Di Luzio M, Arnold J G, Srinivasan R. Effect of GIS data quality on small watershed stream flow and sediment simulations. Hydrological Processes: *An International Journal*, 2005, 19(3): 629-650

31. Malagò A, Pagliero L, Bouraoui F, Franchini M. Comparing calibrated parameter sets of the SWAT model for the Scandinavian and Iberian peninsulas. *Hydrological Sciences Journal*, 2015, 60(5): 949-967

32. Abbaspour K C, Yang J, Maximov I, Siber R, Bogner K, Mieleitner J, ... Srinivasan R. Modelling hydrology and water quality in the pre-alpine/alpine Thur watershed using SWAT. *Journal of Hydrology*, 2007, 333(2-4): 413-430

33. Brown L C, Barnwell T O. The enhanced stream water quality models QUAL2E and QUAL2E-UNCAS: documentation and user manual. Athens, Georgia: US Environmental Protection Agency. Office of Research and Development. *Environmental Research Laboratory*, 1987

34. GRASS 4.1. Reference Manual. *US Army Corps of Engineers. Construction Engineering Research Laboratories, Champaign, Illinois*, 1993

35. Krysanova V, Hattermann F, Wechsung F. Development of the ecohydrological model SWIM for regional impact studies and vulnerability assessment. *Hydrological Processes: An International Journal*, 2005, 19(3): 763-783

36. Krysanova V, Wechsung F, Arnold J, Srinivasan R, Williams J. PIK Report Nr. 69, SWIM (soil and water integrated model). *User Manual*, 2000

37. DHI. MIKE SHE User Manual Voume 1: User Guide. *Danish Hydraulic Institute, Denmark*, 2007

38. Dhami B S, Pandey A. Comparative review of recently developed hydrologic models. *Journal of Indian Water Resources Society*, 2013, 33(3): 34-42

39. Refsgaard J C. Parameterisation, calibration and validation of distributed hydrological models. *Journal of Hydrology*, 1997, 198(1-4): 69-97

40. Butts M B, Payne J T, Kristensen M, Madsen H. An evaluation of the impact of model structure on hydrological modelling uncertainty for stream flow simulation. *Journal of Hydrology*, 2004, 298(1-4): 242-266

41. Gao L, Li D. A review of hydrological/water-quality models. *Frontiers of Agricultural Science and Engineering*, 2014, 1(4): 267

42. Coe M T. Modelling terrestrial hydrological systems at the continental scale: Testing the accuracy of an atmospheric GCM. *Journal of Climate*, 2000, 13(4): 686-704

43. Chow V T. Open Channel Hydraulics. New York: *McGraw-Hill Book Company*, 1973

44. Wallingford H R. ISIS Flow-User Manual. *HR Wallingford and Sir William Halcrow and Partners, Wallingford Software Ltd, Wiltshire, UK*, 1997

45. DHI. Mike-11: a modelling system for rivers and channels, reference manual. *DHI–Water and Development, Horsholm, Denmark*, 2003

46. US Army Corps of Engineers. HEC-RAS river analysis system User's Manual. *Washington, DC, US*, 2010

47. Fluent Incorporated Company. FLUENT 6.3 User's guide. *Lebanon, US*, 2006

48. Hydraulics DHI. MIKE 21 and MIKE 3 flow model hydrodynamic and transport module science documentation. *Copenhagen, Denmark: DHI Water and Environment*, 2009, 3-4

49. Thompson J R. Simulation of wetland water-level manipulation using coupled hydrological/hydraulic modelling. *Physical Geography*, 2004, 25(1): 39-67

50. Morita M, Yen B C. Modelling of conjunctive two-dimensional surface-three-dimensional subsurface flows. *Journal of Hydraulic Engineering*, 2002, 128(2): 184-200

51. Borah D K, Bera M. Watershed-scale hydrologic and nonpoint-source pollution models: Review of mathematical bases. *Transactions of the ASAE*, 2003, 46(6): 1553

52. Melsen L, Teuling A, Torfs P, Zappa M, Mizukami N, Clark M, Uijlenhoet R. Representation of spatial and temporal variability in large-domain hydrological

models: case study for a mesoscale pre-Alpine basin. *Hydrology and Earth System Sciences*, 2016, 20(6): 2207-2226

53. Sloan P G. Modelling surface and subsurface storm flow on steeply-sloping forested watersheds, 1983
54. Cho Y. Development of a watershed modelling selection program and simple equations as an alternative to complex watershed modelling. Doctoral dissertation. *Colorado State University*, 2013
55. Duda P B, Hummel P R, Donigian Jr A S, Imhoff J C. BASINS/HSPF: Model use, calibration, and validation. *Transactions of the ASABE*, 2012, 55(4): 1523-1547
56. SWIM Soil and Water Integrated Model. https://www.pik-potsdam.de/research/climate-impacts-and-vulnerabilities/models/swim/swim-eng.pdf, 2018-6-24
57. Arnold J G, Williams J R, Srinivasan R, King K W, Griggs R H. SWAT: Soil and water assessment tool. *US Department of Agriculture, Agricultural Research Service, Grassland, Soil and Water Research Laboratory, Temple, TX*,494, 1994
58. Priestley C H B, Taylor R J. On the assessment of surface heat flux and evaporation using large-scale parameters. *Monthly Weather Review*, 1972, 100(2): 81-92
59. Ritchie J T. Model for predicting evaporation from a row crop with incomplete cover. *Water Resources Research*, 1972, 8(5): 1204-1213
60. Smedema L K, Rycroft D W. Land Drainage-Planning and Design of Agricultural Drainage Systems. *Cornell University Press, Ithaca, NY*, 1983
61. U.S. Department of Agriculture, Soil Conservation Service. Hydrology. Section 4, Chapter 19. National Engineering Handbook. *USA Government Printing Office*, 1983
62. Kristensen K J, Jensen S E. A model for estimating actual evapotranspiration from potential evapotranspiration. *Hydrology Research*, 1975, 6(3): 170-188
63. Nasr A E, Bruen M, Jordan P, Moles R, Kiely G, Byrne P. Physically-based, distributed, catchment modelling for estimating sediment and phosphorus loads to rivers and lakes: issues of model complexity, spatial and temporal scales and data requirements. In *Paper presented at the National Hydrology Seminar 2004: The Water Framework Directive-Monitoring & Modelling Issues for River Basin Management, November 2004, Tullamore, co. Offaly*. Office of Public Works, 2004

64. Vanderkruk K, Owen K, Grace M, Thompson R. Review of Existing Nutrient, Suspended Solid and Metal Models. *Scientific review for Victorian Department of Sustainability and Environment: Aquatic nutrients, suspended solids, pollutant movement and wetland ecology*, 2010

65. Ward G H, Benaman J. Models for TDML application in Texas watercourses: screening and model review. *Center for Research in Water Resources, University of Texas at Austin*, 1999

66. Tuo Y, Chiogna G, Disse M. A multi-criteria model selection protocol for practical applications to nutrient transport at the catchment scale. *Water*, 2015, 7(6): 2851-2880

67. Kauffeldt A, Wetterhall F, Pappenberger F, Salamon, P, Thielen J. Technical review of large-scale hydrological models for implementation in operational flood forecasting schemes on continental level. *Environmental Modelling & Software*, 2016, 75: 68-76

4. Detailed Water Balance Analysis by Applying Integrated Modelling

Based on the research article:

Waseem, M., Kachholz, F., Klehr, W., & **Tränckner, J.** (2020). Suitability of a Coupled Hydrologic and Hydraulic Model to Simulate Surface Water and Groundwater Hydrology in a Typical North-Eastern Germany Lowland Catchment. Applied Sciences, 10(4), 1281.

https://doi.org/10.3390/app10041281

Abstract: Lowland river basins are characterised by complex hydrologic and hydraulic interactions between the different subsystems (aerated zone, groundwater, surface water), which may require physically-based dynamically-coupled surface water and groundwater hydrological models to reliably describe these processes. Exemplarily, for a typical north-eastern Germany lowland catchment (Tollense river with about 400 km^2), an integrated hydrological model, MIKE SHE, coupled with a hydrodynamic model, MIKE 11, was developed and assessed. Hydrological and hydraulic processes were simulated from 2010 to 2018, covering strongly varying meteorological conditions. To achieve a highly reliable model, the calibration was performed in parallel for groundwater levels and river flows at the available monitoring sites in the defined catchment. Based on sensitivity analysis, saturated hydraulic conductivity, leakage coefficients, Manning's roughness, and boundary conditions (BCs) were used as main calibration parameters. Despite the extreme soil heterogeneity of the glacial terrain, the model performance was quite reasonable in the different sub-catchments with an error of less than 2% for water balance estimation. The resulted water balance showed a strong dependency on land use intensity and meteorological conditions. During relatively dry hydrological years, actual evapotranspiration (ETa) becomes the main water loss component, with an average of 60%–65% of total precipitation and decreases to 55%–60% during comparatively wet hydrological years during the simulation period. Base flow via subsurface and drainage flow accounts for an approximate average of 30%–35% during wet years and rises up to 35%–45% of the total water budget during the dry hydrological years. This means, groundwater is in lowland river systems the decisive compensator of varying meteorological conditions. The coupled hydrologic and hydraulic model is valuable for detailed water balance estimation and seasonal dynamics of groundwater levels and surface water discharges, and, due to its physical foundation, can be extrapolated to analyse meteorological and land use scenarios. Future work will focus on coupling with nutrient transport and river water quality models.

Keywords: groundwater–surface water interaction; integrated hydrological–hydraulic modelling; lowland hydrology; MIKE SHE; MIKE 11; Tollense river; water management.

4.1. Introduction

Hydrological processes in moderate climate lowland catchments can be complicated due to complex surface water (SW) and groundwater (GW) interactions, and due to this complexity, precise hydrological water balance information is a prerequisite to develop management practices for the sustainable use of water resources. Hydrological research and forecast has become increasingly important due to the growing problems with the available water resources, and due to this reason, the hydrological forecasts have been modernised, extending from simple flood predictions to detailed water management decisions and practices that require extensive hydrological processes information [1–4]. Integrated hydrological models play an essential role by providing the necessary information regarding biological, physical, and chemical processes and their interactions within a catchment [5,6]. In general, the temporal and spatial variations of GW and SW resources are imprecisely known which effects the proper management of water resources [7–9]. Physically-based dynamically-coupled SW and GW hydrological models are increasingly being used to examine the environmental interactions [10], transport of solute [11], flood modelling [12], and understanding of catchment hydrology [13–18]. A good forecast of an integrated hydrological model does not only depend on the code but also on the ability of the modelling tool to adequately characterise the complex surface and subsurface hydrological processes and parameter distributions, which otherwise results in greater uncertainty and higher degree of errors [19,20]. Lowlands are characterised mainly with high GW levels, low hydraulic gradients, and flat topography. This may lead to direct hydraulic interactions between the different subsystems which are not adequately described by pure hydrologic model approaches. Human interventions such as land use, artificial drainage, GW abstraction via pumps, river hydraulic structures, etc., also effect the natural water balance in lowlands. The complex SW and GW interactions can be reliably considered by bi-directionally-coupled hydrologic–hydraulic models of both systems. However, due to their complexity and numerical challenges, those models are rarely applied, so far. In this study a physically-based distributed hydrological model, MIKE SHE, coupled with a hydrodynamic model, MIKE

11, was set-up and calibrated for a typical lowland catchment in moderate climates, the Tollense River in the north-east of Germany. The Tollense river catchment was selected as study area in collaboration with the regional environmental protection agency (StALU-MS) due to its typical characteristics and related typical water management challenges (flood protection and maintenance of water infrastructures vs. near natural conditions, agricultural impact on water quality and balance) and the availability of the sufficient monitoring data. Dominant land use in the Tollense catchment is intensive agriculture. Large areas are provided with artificial drainage/GW abstraction pumps, while the Tollense river is equipped with two weirs named as Osten and Tückhude to regulate the river flow. The artificial drainage is applied to lower the GW level for agricultural use, especially in the spring months, and accelerates flow and transport of nutrients in the catchment. Depending on the fertilizer application, plant growth state and the meteorological conditions fertilizer applied to the crops is partly washed off in GW and SW, leading to increased nutrient concentrations (namely nitrate) in both systems. Weirs serve opposite to the drainage by raising the SW levels on their upstream side (u/s), and results in SW contribution to the GW. The Tollense river also observes a back water effect at its confluence with the river Peene in Demmin, due to low hydraulic gradients influenced by the Baltic Sea. In the last decade, the region has faced strongly varying meteorological conditions, with very wet years and partial flooding of agricultural areas (e.g., in 2011 and 2017) and very dry years with partial drought (e.g., in 2018). This illustrates that the development of adaptive water management is challenging and requires a deterministic model to forecast probable climate and land use scenarios and to assess the effect of water management options. Before deciding for the chosen model combination, four different process models were reviewed, which integrate GW and SW processes: SWAT (soil and water assessment tool), HSPF (hydrological simulation program—FORTRAN), SWIM (soil and water integrated model), and a bi-directional coupling of MIKE SHE and MIKE 11. By focusing mainly on moderate climate lowland catchments with intensive agriculture, high GW tables and decreased retention times, these models were compared on the basis of their data requirement, desired complexity level, and their ability to simulate relevant hydrologic and hydraulic processes. Both SWAT and MIKE SHE are able to simulate the desired hydrological processes shown in **Figure 4.1**, but in case of simulating the hydraulic structures and their data in comparison to HSPF and SWIM. SWIM and SWAT are based on similar governing equations and input data requirements, but SWIM does not simulate ponds, lakes, wetlands, and drainage systems. Both HSPF and SWIM do not provide a satisfying solution to include pump flow drainage. HSPF is more suitable to study the fate and transport of nitrogen in unsaturated, saturated, and surface flow zones. In order to simulate the backwater effect and control structures and their operational strategies, all these models need to be coupled with hydrodynamic models. Here, MIKE SHE is advantageous, since it provides a ready coupling interface to the hydrodynamic model MIKE 11, which can simulate backwater effects, hydraulic structures (e.g., weirs, gates, etc.), and their operations [21–32]. MIKE SHE is a physically-based distributed hydrological model that allows the integrated modelling of hydrological processes and can simulate the SW and GW interactions within a catchment [4,5]. MIKE SHE has the ability to simulate the catchment areas ranging from less than 1 km^2 [33–36] to thousands of km^2 [37–39]. MIKE SHE water movement module consists of six components that describe the hydrological cycle, including precipitation/interception, evapotranspiration (ET), saturated zone (SZ), unsaturated zone (UZ), overland (OL) flow, and exchange between SW and GW [36]. As the above described hydrologic, hydraulic, and infrastructural conditions apply large areas in the North and West of Europe, North Western, North America, and (with different meteorological conditions) also in Asia, the chosen model combination should be interesting for these areas too.

The research main questions of the present study include:

1. Possibility to satisfyingly incorporate all relevant processes and boundary conditions and to holistically calibrate the model.
2. Quantification of the meteorological effects on water balance components and the exchange of GW and SW during dry and wet hydrological years.
3. Effects of weather variations on seasonal dynamics of GW levels and river discharges in lowlands.
4. Use of physically-based distributed coupled models and their ability to simulate lowlands with moderate climatic conditions.

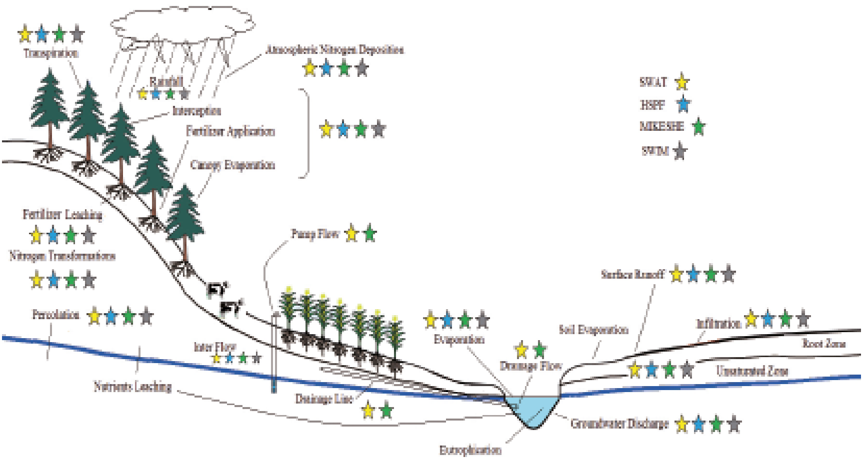


Figure 4.1 Ability of selected modelling tools to simulate the desired hydrological processes in north-eastern Germany lowland catchment based on literature [40].

4.2. Materials and Methods

4.2.1. Study Area

Tollense river basin is an example of a typical lowland catchment located in north-eastern Germany (**Figure 4.2**). The Tollense river starts as an outflow of the lake Tollense (at the city Neubrandenburg) Neubrandenburg) and flows about 68 km through a glacier terrain to its confluence with river Peene in the small town Demmin. The presented study was performed on the downstream section of the Tollense river with an approximate length of 30 km, staring from Klempenow to Demmin, with an average catchment area of about 400 km2. The Tollense river catchment is provided with artificial drainage and is primarily used for agricultural activities. Land use maps were developed in ArcGIS based on aerospace images provided by the Rapid Eye Science Archive platform. Supervised image classification performed in ArcGIS resulted that the study area consisted mainly of 18% forests and 70% arable land and pastures [40].

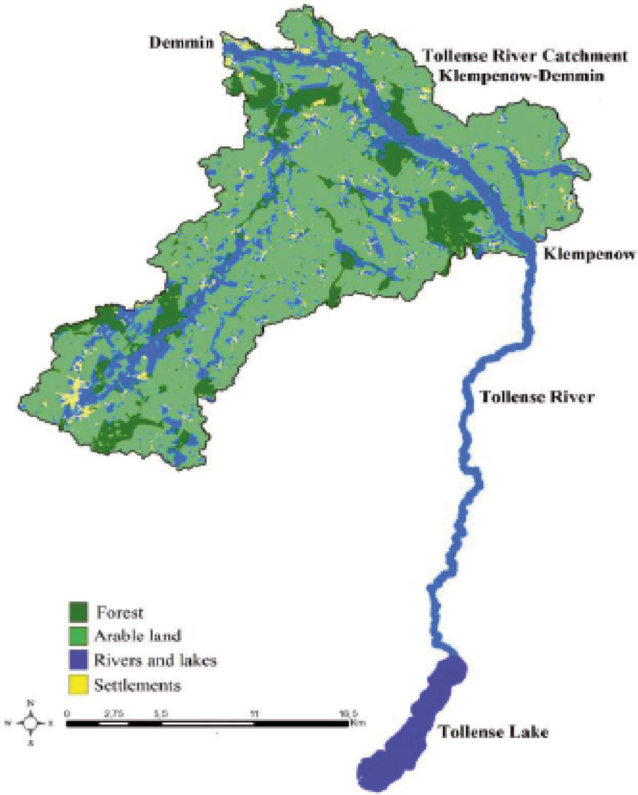
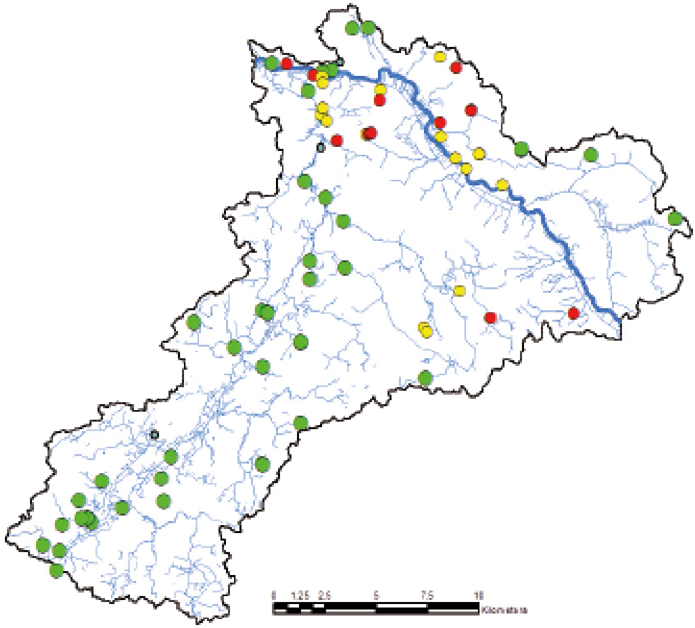


Figure 4.2 Tollense River originating from Tollense lake in Neubrandenburg towards its downstream end in Demmin, and land use in Tollese river catchment from Klempenow to Demmin. © Rivers, lakes, and land use data was provided by "State office for the Environment, Nature Conservation and Geology Mecklenburg-Vorpommern" (LUNG-MV) [40].

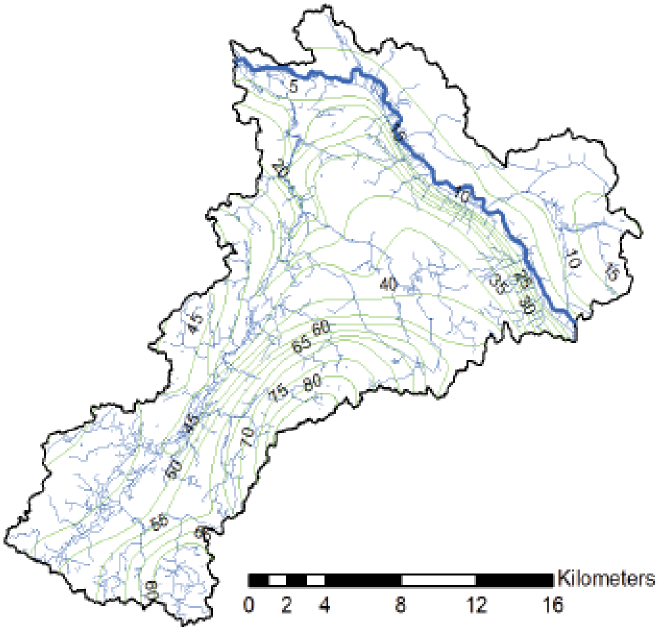
4.2.2. Data Collection

4.2.2.1. Groundwater Data

To conduct a successful model calibration, it was necessary to improve the existing database of observed GW levels by continuous monitoring. For this, continuous GW data loggers were installed at 7 boreholes in the catchment with an hourly log rate, starting from November 2016 to the end of April 2018. Boreholes for data logger installation were selected on the basis of their geographic location, accessibility, functionality, and protection from theft and animals (**Figure 4.3** (left)). Borehole functionality was determined based on refill tests performed in collaboration with StALU-MS, being incharge of the institutional GW monitoring. Some of the boreholes were identified as clogged due tolack of operational management and some were not found due to misleading coordinates. **Figure 4.3** (right) shows the constructed GW contours in the study area based on recorded GW levels via data loggers. These were further used as an initial condition during simulation.



(a)

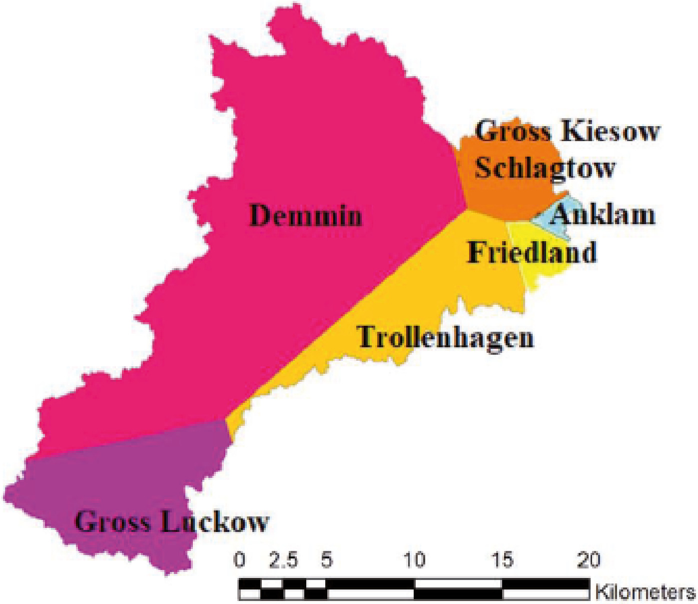


(b)

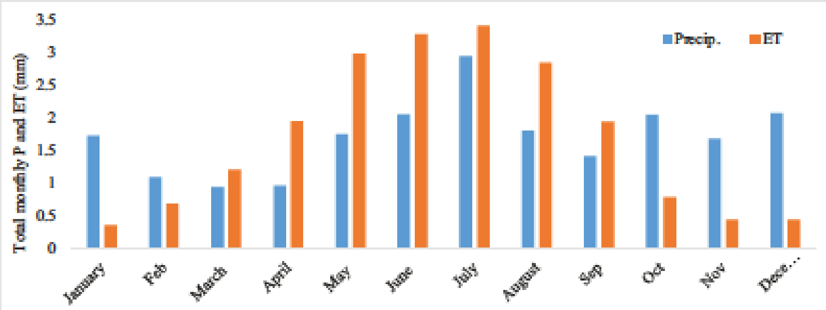
Figure 4.3 (a) Summary of the available boreholes and their functionality status in the study area, where Green circles are the boreholes found and working; yellow circles are the boreholes found but not working; and red circles are the boreholes not found; (b) constructed the groundwater contours in study area.

4.2.2.2. Climate Data

Accumulated daily precipitation data ranging from 2010 to 2018 was collected for 6 climate stations named as Demmin; Gross Kiesow Schlagtow; Anklam; Friedland; Trollenhagen; and Gross Luckow, located within or nearby the defined Tollense river catchment. The Thiessen polygon interpolation method was used to divide the catchment area under each climate station shown in **Figure 4.4** (up). Penman Monteith method [41] was used for potential evapotranspiration (ETp) calculation and it requires relative humidity, cloud cover, wind speed, and daily maximum and minimum wind temperatures to calculate the ETp [42]. For ETp calculation, data from the climate station named as "Demmin" was used as it was the nearest climate station where all the required data was available to calculate the ETp. **Figure 4.4** (down) shows the average monthly ET and precipitation rates for the climate monitoring station "Demmin" from 2010 to 2017. MIKE SHE uses the Kristensen and Jensen method [43] to compute the Eta on the basis of specified ETp rates and soil moisture available in the root zone.



(a)



(b)

Figure 4.4 (a) Catchment area under each climate station by using Thiessen Polygon interpolation method and (b) average monthly precipitation and ET at Demmin from 2010 to 2017.

4.2.2.3. Land Use Data

Land use, shown in **Figure 4.2**, is based on Rapid Eye Science Achieve images and an image classification was performed in ArcGIS to obtain the land use maps. Land use was classified as arable land, wetlands, grassland, industrial areas, forests, small gardens, settlements, concrete surfaces, roads, water facilities, and miscellaneous, based on the image classification results. **Table 4.1** shows the summary of the data used in this study and the related sources from where the data was obtained. Leaf area index (LAI) based on project "Communal waters collective development in urban areas" (KOGGE) [44] in monthly temporal resolution is shown in **Figure 4.5** and average root depth (RD) on seasonal temporal resolution [45] is shown in **Table 4.2**.

Table 4.1 Summary of the data used in this study and the sources from where the data is obtained.

Type of data	*Sources*
Digital elevation model (DEM)	LUNG-MV
Land use	Rapid Eye Achieve images
Precipitation	German weather services (DWD)
Potential evaporation (ETp)	Penman Monteith method [41]

Leaf area index (LAI)	Project KOGGE [44]
Root depth (RD)	ATV-DVWK-M 504 [45]
Topography	LUNG-MV
Soil properties	LUNG-MV
Soil Profiles	LUNG-MV
Manning Roughness Coefficient	Literature
Geological data	LUNG-MV
Piezometer levels	LUNG-MV
River Network	LUNG-MV
River Cross-sections	ADCP measurements and DEM
River flow	Research- Project "BOOTmonitoring"

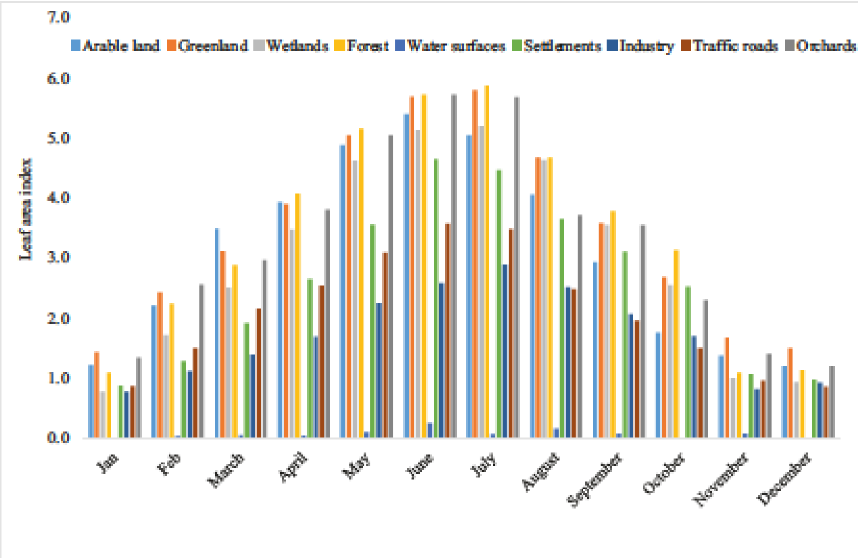


Figure 4.5 Average monthly variation of leaf area index used in Tollense river basin [44]

Table 4.2 Average root depths during the summer and winter season in Tollense river basin [45]

Land use class	Avg. RD (summer) (mm)	Avg. RD (winter) (mm)
Arable land	600	200
Wetlands	300	300
Greenland	300	100
Industry	600	600
Forest	800	800
Orchards	500	500
Settlements	600	600
Parking surfaces	600	600
Water surfaces	0	0

4.2.3. MIKE SHE Model Setup

SHE model uses different process-oriented components to describe the hydrological cycle by coupling the UZ and SZ, as shown in **Table 4.3**. MIKE SHE uses three different methods to account for UZ flow simulations, named as two-layer UZ method, Richards equation, and gravity flow method. The MIKE SHE model uses the Kristensen-Jensen method [43] to estimate the ET and interception processes by using climatic and vegetative data. Due to the computational time constraints, a simplified two-layer water balance method was used to estimate the UZ flow based on the formulation provided by Yan and Smith [46]. The main objective of the module is to compute the ETa and the volume of GW recharge and is mainly advantageous in areas with a shallow GW table (e.g., wetlands where the ETa is nearly equal to the reference ET rate). In catchments with higher UZ depths, the two-layer method does not precisely characterise the UZ flow dynamics. The two-layer UZ method considers only the average conditions and does not account for the UZ hydraulic conductivity and soil moisture content relationship, and hence does not consider the soil ability to transport water to the plant roots. That means if sufficient water is available in the root zone it will be available for ET. However, by calibrating the input parameters, the two-layer UZ method performs quite well in most of the conditions. The defined method takes into account the processes of canopy interception, ponding, and ET and considers the whole UZ to consist of two layers representing average conditions in the UZ, where vegetation data is defined as LAI and RD. The soil properties are defined by a constant infiltration capacity, soil moisture content at wilting point, field capacity, and saturated water content. The two-layer UZ method fulfils the main objectives to account for ETa and the SZ recharge mainly required in this study. The MIKE SHE model uses the 3D-Boussinesq equation to simulate the SZ flows [36], while river hydrodynamics (stage and discharge) are defined by using the simplified diffusion wave approximation of the Saint-Venant equation.

Table 4.3 MIKE SHE water modelling components and related numerical solutions [3,5,47,48].

Component	Numerical methods
◦ ET	◦ Kristensen and Jensen method [43] ◦ Two-layer water balance method [46]
◦ UZ Flow	◦ Richards equation ◦ Gravity flow ◦ Two-layer water balance
◦ OL-Flow	◦ 2D-finit difference diffusive wave equation
◦ Channel Flow • Flow Routing	◦ 1D-Saint-Venant equation • No routing • Muskingum method • Muskingum-Cunge method
◦ SZ Flow	◦ 3D-Finite difference method ◦ Linear reservoir method

Due to the limited ability of MIKE SHE to simulate the hydraulic structures and their operations, MIKE 11, a 1D-hydrodynamic model, was used to incorporate the control structures such as the weirs, sluice, culverts, gates, etc., and their time varying operations. The MIKE SHE model used in this study uses the "ETRS_1989_UTM_Zone_33N_8stellen" coordinate system in metric units. The performance of the hydrological model was evaluated at different grid sizes (20, 50, 100, 200, and 300 m) and a spatial resolution of 100 m was selected as an optimum compromise between computational time and model performance. The model area of 400 km^2 was divided into 100 x 100 m computational cells to represent the spatial variations in soil, land use, and geology. Model area was divided into computational grids in order to have the numerical solutions of the governing equations [49–51]. DEM with a resolution of 5 m was used to represent the topography in the study area and was provided by LUNG-MV. In case of temporal discretization, the computational time steps were chosen in such a way that OL-flow computational time step is always less or equal to the UZ time step, while the UZ time step is always less or equal to the SZ time step. During the temporal discretization, selected time steps are always critical for minimizing the water balance errors [3]. Aquifer BC used in this study are explained in **Figure 4.6**; zero flux BC was selected where lateral flows were expected to be minimum based on the GW contours and topographical characteristics, while in case of gradient BC, selected gradient values were estimated based on GW contours. The two-layer UZ method was used to predict the flow through or within the UZ. Soil data and Van Genuchten parameters [52,53] were obtained from LUNG-MV and were used to develop the detailed soil map. The soil column vertical discretization was kept constant in the entire model with a minimum soil thickness of 0.5 cm at the ground surface to comprehensively quantify the nonlinear evaporation and transpiration to the maximum vertical discretization of 1 m at the model outer depth. The SZ was characterised by three layers of geology and a three-dimensional Boussinesq equation was used to estimate the SZ flows. The depth of the aquifer was estimated based on geological data obtained from 60 boreholes available in the study area, and these interpolated GW levels were used as SZ initial conditions. Fine tuning of vertical and horizontal hydraulic conductivities of geological layers played a vital part in the successful model calibration.

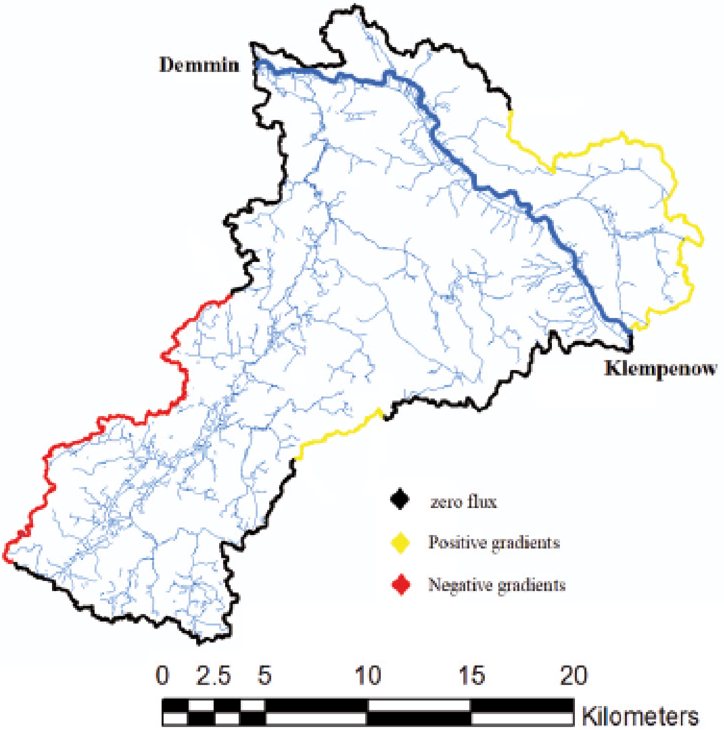
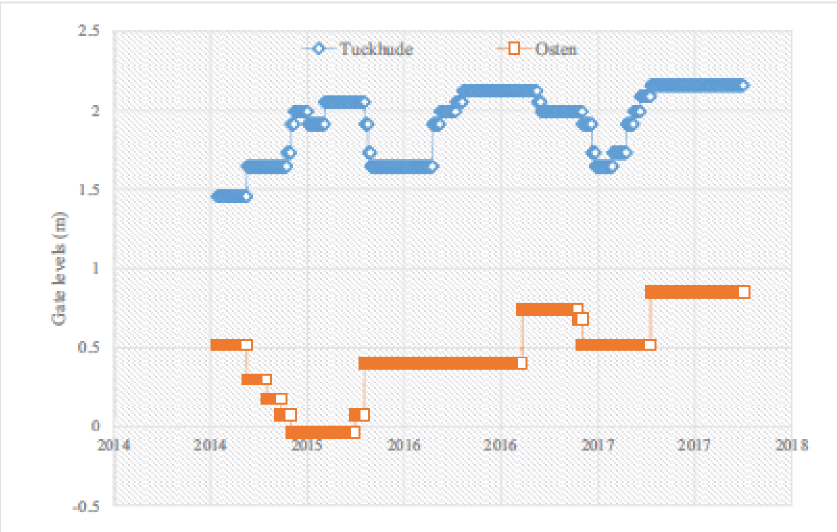


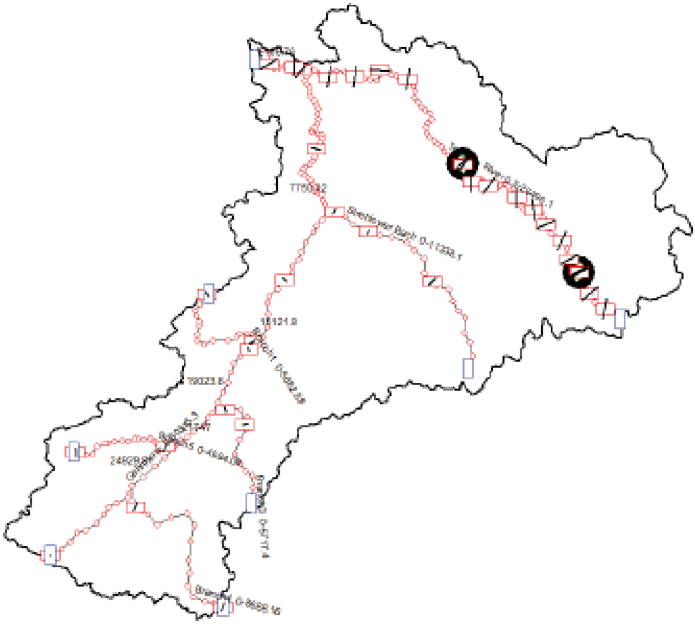
Figure 4.6 Boundary conditions used in the SZ where black line is zero flux BC, yellow line is positive gradient BC, and red line is negative gradient BC.

4.2.4. Coupling of MIKE SHE and MIKE 11

MIKE 11 uses complete dynamic wave formulation of the Saint-Venant equation and is able to simulate the wide range of hydraulic structures such as weirs, culverts, gates, and bridges, etc. The river network in the defined catchment containing the main Tollense River, its tributaries, and control hydraulic structures are shown in **Figure 4.7** (right). A fully-dynamic 1D-Saint-Venant equation was used to describe channel flow in the Tollense river and its tributaries. Two weirs, named as Osten and Tückhude, equipped with adjustable gates and variable operational strategy, were modelled in MIKE 11, as shown in **Figure 4.7** (left). Channel cross-sections were based on ADCP surveys conducted at 29 locations along the Tollense river, in the river section starting from Demmin (downstream) to Klempenow (upstream). The river bed was considered fully connected with the SZ, as a result the exchange between the river and the GW aquifer was defined by the hydraulic conductivity of the aquifer instead of the river bed material. In case of the Tollense River, time series of discharge at daily temporal resolution was inserted as an upstream BC at Klempenow and average water levels were used as a downstream BC at Demmin. The data used in the present study in the MIKE11model includes river network, control strategy of hydraulic structures, river cross sections, hydraulic structures and their geometry, seasonal Manning's roughness coefficients, river boundary conditions, and hydrodynamic parameters.



(a)



(b)

Figure 4.7 (a) Weir gate openings from reference level at Tückhude and Osten. (b) MIKE 11 model of Tollense river and its tributaries, channel cross sections (red rectangles) and control structures (black circles).

A dynamic coupling of MIKE SHE and MIKE 11 considers the exchange of data among the two models after every computational time step and their coupling is done by means of line segments, serving as river links in MIKE 11 to the adjacent MIKE SHE grids. River links are created for coupled reaches and their locations are defined automatically from MIKE 11 river point coordinates that define the river branches of a hydrodynamic model. During simulation, the water levels within the coupled reaches are transported from MIKE 11 H-points to the adjacent MIKE SHE river links, as shown in **Figure 4.8**. In return, MIKE SHE estimates the OL-flow to each river link as an exchange between the neighbouring grid squares and the river aquifer, and finally these terms are sent back to the corresponding MIKE 11 H-points as an outflow or inflow for the following computational time step. If the water level in a grid square gets higher than its topographic level, it is considered as flooded, and as soon as a grid square gets flooded MIKE SHE computes infiltration, seepage, OL-flow, and ET in the similar manner as for a grid square with SW ponding resulting from precipitation and surface runoff, or the water table intercepting the ground surface [54].

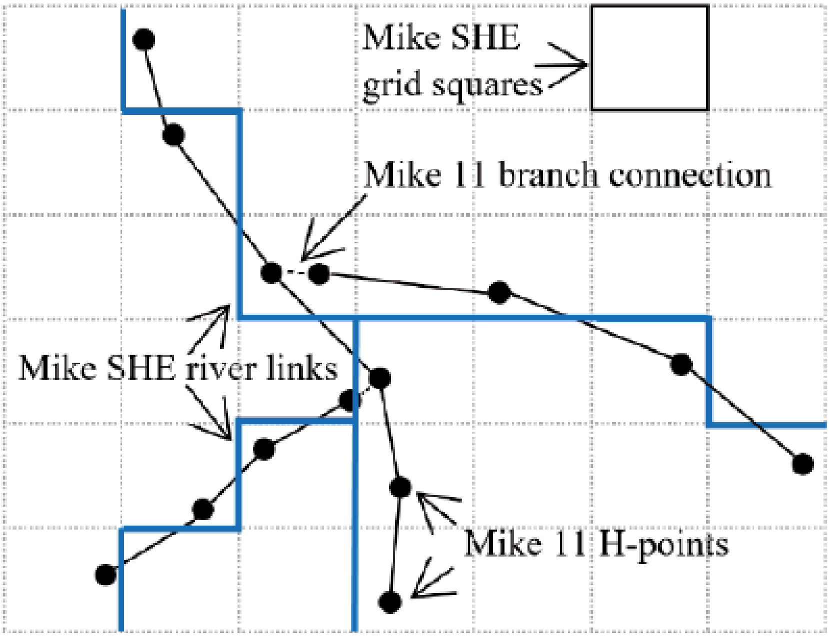


Figure 4.8 Coupling scheme of a hydrological model MIKE SHE with a hydrodynamic model MIKE 11based on literature [54].

4.3. Results

4.3.1. Sensitivity Analyses and Calibration and Validation Procedure

Sensitivity analyses were performed in order to assess the most sensitive parameters for Tollense river catchment model calibration and were performed by changing different parameters within their allowable range most sensitive parameters were selected for the calibration process. Sensitivity analyses was performed by adjusting only one parameter during a simulation while others parameters were kept unchanged during each sensitivity test so that sensitivity of each parameter can be evaluated. **Table 4.4** shows the considered variables and their definitions in the MIKE SHE and MIKE 11 model. Due to the close interaction of GW and SW, calibration of GW levels and SW discharges was conducted in parallel. Especially the calibration of GW level became challenging to the extreme soil heterogeneity, which is typical for glacial soils. Auto calibration was not applied in this study, as the intention was not to achieve an optimum fit between the observed and simulated data, as the model setup without auto calibration provides better process understanding and helps to identify the model deficiencies. Validation is a procedure to ensures that a system satisfies the stated functional intent of the system and is performed after achieving the calibration.

Table 4.4 Variables used for sensitivity analyses and their definitions in MIKE SHE and MIKE 11.

Parameter	**Definition**
Drainage	• Depth to subsurface drain
Groundwater	• Initial potential heads • Groundwater influxes and flow gradients • Saturated hydraulic conductivity • Depth of geological layers
Channel flow	• Manning roughness coefficient

Calibration is a process of model testing with known inputs and outputs and is used to estimate or adjust different parameters. The calibration process was initiated after the sensitivity analysis and following calibration techniques were applied for the different river flow calibration outcomes. In case 1—when the model was unable to simulate the peak flows, a careful review of the data was done for both the precipitation and river flow, as this happens normally due to the reason that either the rainfall station is not representative or due to the malfunctioning of the precipitation or flow gauges. In case 2—when the model continuously over predicted the flow, ET, soil water content, percolation, and GW recharge rates were adjusted. In case 3—where simulated flow followed the observed flow dynamics but lags the actual flow consistently, river bed leakage coefficient rates and Manning's roughness coefficient were adjusted. In case 4—when the model over predicted the peak flows but under predicted the average normal river flows, infiltration rate, interflow, and base flow recession parameters were adjusted.

The coupled MIKE SHE and MIKE 11 model was calibrated by using the measured GW heads at seven selected GW observation wells shown in **Figure 4.9**, for the period ranging from November 2016 to April 2018. River flow calibration was based on flow measurements performed by StALU-MS and University of Rostock along the Tollense river at four different chainages in the river section from Klempenow to Demmin. Calibrated GW level and surface flow results are presented in **Figure 4.10** and **Figure 4.11**, respectively, for a period of nine years starting from 2010 to 2018. During the calibration process, hydraulic conductivity, BCs, roughness coefficient, and specific yield were adjusted to calibrate the coupled MIKE SHE and MIKE 11 model and their calibrated values are shown in **Table 4.5**.

Table 4.5 Parameters used for calibration and their range and selected values

Parameters	Initial value	Range	Final value
Hydraulic conductivity	A: $1*10^{-5}$ B: $1*10^{-8}$ C: $1*10^{-10}$	$1*10^{-10}$ - $1*10^{10}$ $1*10^{-10}$ - $1*10^{10}$ $1*10^{-10}$ - $1*10^{10}$	$1*10^{-4}$ $1*10^{-7}$ $1*10^{-10}$
Specific yield	A: 0.25 B: 0.2 C: 0.1	$1*10^{-10}$ - $1*10^{10}$ $1*10^{-10}$ - $1*10^{10}$ $1*10^{-10}$ - $1*10^{10}$	0.266 0.20 0.108
Boundary condition - gradients	+ve gradients: 0.0015 -ve gradients: 0.004	0.009 - -0.009 0.009 - -0.009	0.0036 -0.004
Manning roughness coefficient M	Natural channel: 10 Weirs or concrete surfaces: 80	10-25 80-100	15 85

4.3.2. Groundwater Dynamics (Calibration and Validation)

Simulated GW levels were calibrated against hourly observed GW data obtained from the data loggers installed in the study area for the period ranging from November 2016 to April 2018. In the present study, GW data from seven boreholes located in the Tollense catchment were used. Borehole HySzw 141/1989 is located near to the Tollense River, HyStav 7/2005 and HyBorr 106/1985 are directly at the bank of Gemkow tributary, while other boreholes are located at banks of small tributaries present in different sub catchments of the Tollense river basin shown in **Figure 4.9**. In this study, the 5 GW boreholes HyBorr 105/1985; HyStav 2/2005; Hy Borr 106/1985; HyStav 7/2005; HySzw 141/1989 were used to achieve calibration. Remaining two boreholes Hy Kris 1/2008; Hy

Top 1/2008, where longer GW monitoring data was available were used for validation of the coupled hydrologic and hydraulic model.

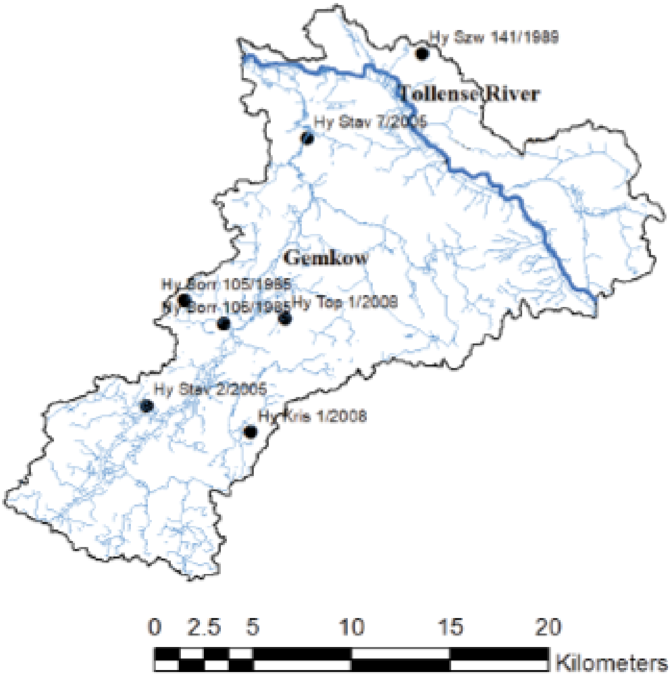


Figure 4.9 Selected boreholes used for groundwater level calibration.

The statistical performance of the calibration and validation process of a coupled MIKE SHE and MIKE 11 model in terms of predicting the GW dynamics is shown in **Table 4.6**, whereas **Figure 4.10** shows the comparison of simulated and observed GW levels at the selected seven borehole locations located in different sub catchments of the Tollense river basin. A good agreement was observed between simulated and observed GW levels. But simulated GW reacts more dynamically. A probable reason is the selection of too course spatial and temporal discretization to simulate strong soil heterogeneity of the catchment. As expected, higher GW level occurs during the winter season, then dropping to lower levels during the summer season with increasing ET. In general, the coupled model underestimates the GW levels during the high recharge periods, but the performance of the model was not equally comparable at all the observation locations. Due to the rather shallow GW tables, there is a strong relationship spatially and temporally between the precipitation and resulted simulated GW levels. GW elevations react dynamically to local precipitation events. Boreholes located in the vicinity of the climate station "Demmin" showed that the average simulated GW elevations across the middle and downstream section varies up to around 0.15 m during an extra ordinary precipitation event that occurred in October 2017. Coupled model performance was evaluated by using mean absolute error, root mean square error, correlation coefficient, and standard deviation residuals. Initially climate parameters were adjusted according to the basin climate conditions and after that the calibration process was focused mainly on horizontal and vertical conductivity and specific storage of the SZ parameters. As a result, the calibration process includes seasons with different GW dynamics due to variation in rainfall patterns and resulted varied GW levels. Specific yield and GW gradients turned out to be the most adjusted parameters, as boundary gradients normally determine the GW influx, while specific yield defines the dynamic response of the GW system, hence both have an impact on estimated water balance.

Table 4.6 Statistics of the objective function for groundwater level calibration.

Calibration				
Groundwater well ID	**MAE(m)**	**NSE**	**R (Correlation)**	**STDres**
HyBorr 105/1985 – LOCID # 466	1.467	0.60	0.845	0.352
HyStav 2/2005 – LOCID # 42	1.159	0.63	0.749	0.131
Hy Borr 106/1985 – LOCID # 467	0.478	0.61	0.786	0.351
HyStav 7/2005 – LOCID # 47	2.137	0.64	0.500	0.096
HySzw 141/1989 – LOCID # 670	1.080	0.58	0.868	0.414
Validation				
Groundwater well ID	**MAE(m)**	**NSE**	**R (Correlation)**	**STDres**
Hy Kris 1/2008 – LOCID # 37	5.987	0.65	0.7435	0.439
Hy Top 1/2008 – LOCID # 67	1.500	0.67	0.646	0.411

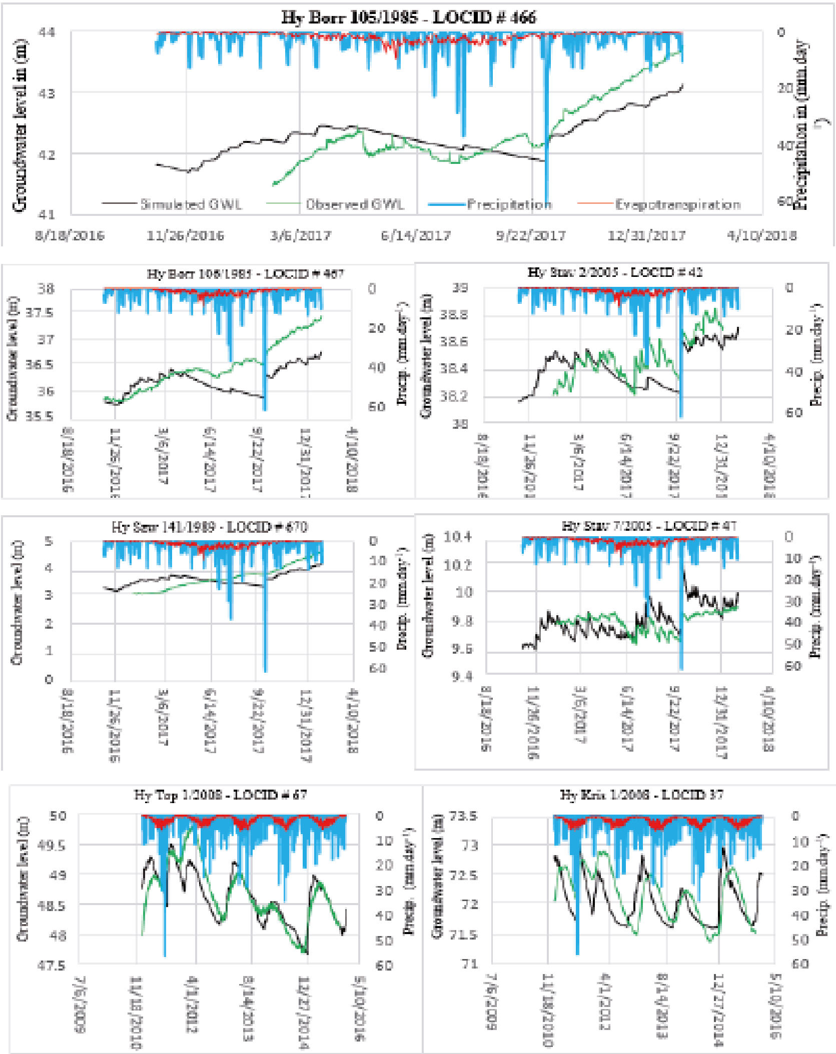


Figure 4.10 Observed (green) and calibrated (black) groundwater heads in Tollense River catchment with rainfall (blue) and ET (red) rates.

4.3.3. Stream flow Dynamics

The purpose behind the river flow calibration and validation was to compare simulated and observed hydrographs at the catchment outlet as adjusted of parameters for GW calibration has a direct impact on surface flows. The outflow hydrograph has the potential of representing the integrated effect of the hydrological response of the catchment as a whole. Flow measurement campaigns were launched under the BMBF project named as "Boat monitoring" [55], and flow was measured at different chainages along the river Tollense. River flow was calibrated at four chainages at 270, 1365, 7048, and 23,341 m from the downstream end of the Tollense river. The statistic quality criteria concerning river dynamics (mean absolute error, root mean square error, correlation coefficient, and standard deviation residuals) are summarised in **Table 4.7**. The simulated results were satisfactory and were able to predict the general characteristics of the discharge time series at specified chainages. Simulated hydrographs underestimate the river flows during the observed low flow periods, while overestimate the river flows during the observed peak flow discharges in the river Tollense. The probable reason behind this discrepancy is the artificial drainage in the catchment. Artificial drainage was constructed based on DEM lowest points and does not fully represent the real installed drainage system in the catchment. GW levels lower than artificial drainage makes the drainage ineffective and results in small GW contribution to the river. For periods with GW levels higher than constructed drainage in MIKE SHE, drainage becomes effective and may contribute more to the river Tollense in comparison to reality. Moreover, average rainfall over the entire area in each polygon assigned to its respective climate station, average hydraulic conductivity of an entire geological layer, and drainage time constants also effects the GW contribution to the SW flows, and cause differences between observed and simulated river discharges.

Table 4.7 Statistics of the objective function for river flow calibration.

Stream flow observation points	MAE (m)	NSE	R (Correlation)	STDres
Chainage 270 m from d/s	0.998	0.90	0.974	1.190
Chainage 1365 m from d/s	1.680	-126.90	1	0.412
Chainage 7048 m from d/s	0.813	0.94	0.999	0.118
Chainage 23341 m from d/s	0.182	0.95	0.999	0.132

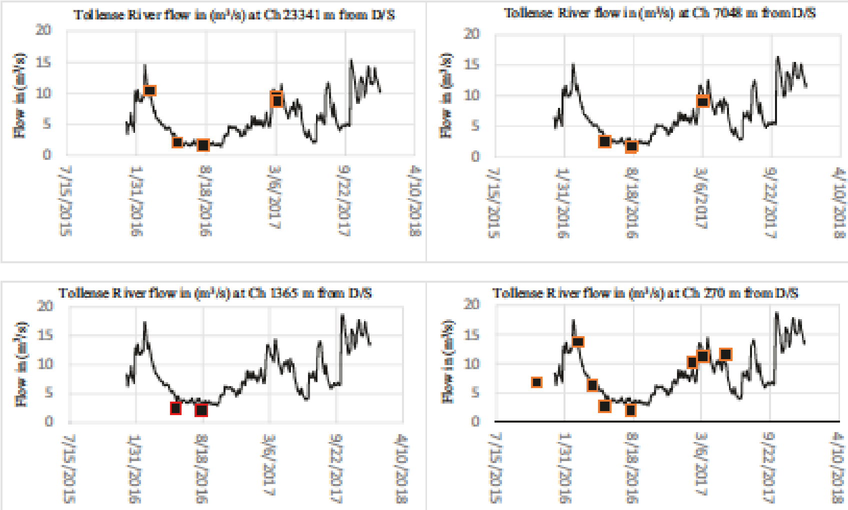


Figure 4.11 Observed (black squares) and simulated river (continuous black line) flows in Tollense River catchment.

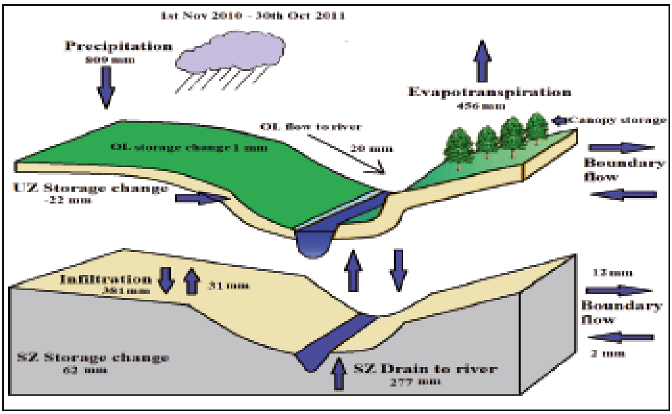
4.3.4. Water Balance

A water balance estimation was performed following the calibration process as the interest of this study was to get a better insight into the interaction of the different subsystems and hydrological processes in highly GW influenced lowland river basins. The water balance was performed for the whole calibration period and additionally for each hydrologic year, which is defined between 1st October to 30th September of the next year in Germany. The total water input into the model was via precipitation and surface and subsurface inflow, which was further divided into ET, runoff and change in storage, and GW and SW interactions. Water balance error was calculated after balancing all the major hydrological components that includes precipitation, ET, runoff, surface and subsurface inflow, and change in storage. With a water balance error of less than 2% during the calibration period, the total estimated water balance is satisfyingly good.

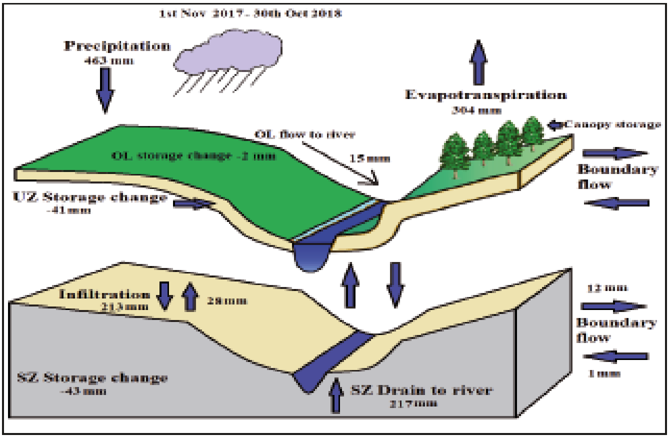
Total water balance: Overall water balance results shown in **Figure 4.12** (a) clearly show that a considerable portion of precipitations is going back to the atmosphere as an ET loss that represents approximate average of 60% of the total precipitation. Areas of small lakes, ponds, and forests contribute to the major part of ET loss. GW contribution to the SW flow is around 30%–35% via drainage, while SZ storage has decreased over the past nine simulated years, and this is evident in the simulated GW levels in the lowland catchment. Tollense river catchment has a very small cross boundary SZ inflow and GW storage is mainly dependent on local meteorological conditions, such as precipitation and ET.

In the lowland catchment, the UZ is very shallow during the wet seasons. Due to this, infiltration and ET are vital processes that control the rate of recharge. Results illustrate that the SZ gains approximately 30%–40% of total precipitation, out of which a major portion is drained to the river via artificial drainage available in the study area.

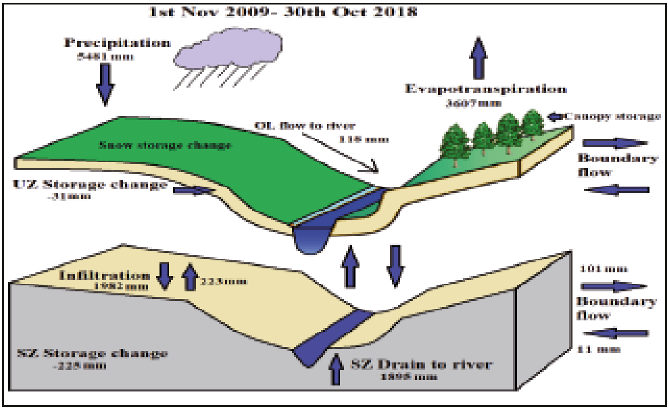
Water balance in wet and dry hydrological years: The water balance results for a wet hydrological year (2010–2011) and dry hydrological year (2017–2018) are shown in **Figure 4.12** (b, c). During the wet hydrological year, ET is 56% of total P, while drainage contributes 34% of P into the river Tollense with a positive GW storage. During the dry hydrological year, ET raises up to 65% of total P with a raised drainage contribution of 46% in to the river flows, resulting in a negative GW storage. The water balance results show that GW is a main contributor to the surface flows during low rainfall or partial drought periods and balance SW discharges in the Tollense river catchment.



(a)



(b)



(c)

Figure 4.12 Water balance for Tollense river catchment (400km^2) during wet hydrological year 2010-11 (a); dry hydrological year 2017-18 (b); total water balance from 2010-2017 (c). All figures are in millimetres, where positive and negative storage change represents the ascending and descending change in water stored in SZ and UZ.

Figure 4.13 shows yearly water balance components for 8 hydrological years starting from 2010 to 2017. GW recharge was estimated from the exchange between SZ and UZ. The water balance results need to be examined cautiously and water balance results in moderate climate lowlands as it is controlled by climate variations and catchment characteristics. To ease the comparison between different components, all numbers in the **Figure 4.13** are in units of mm. Following equation (1) can be applied to convert these units into volume units of m³/time.

$$N=\frac{\frac{n}{1000}*A}{t} \qquad [1]$$

Where; N =value inm³/year; n = value in mm; A = model area in m²; t = simulation time period in years

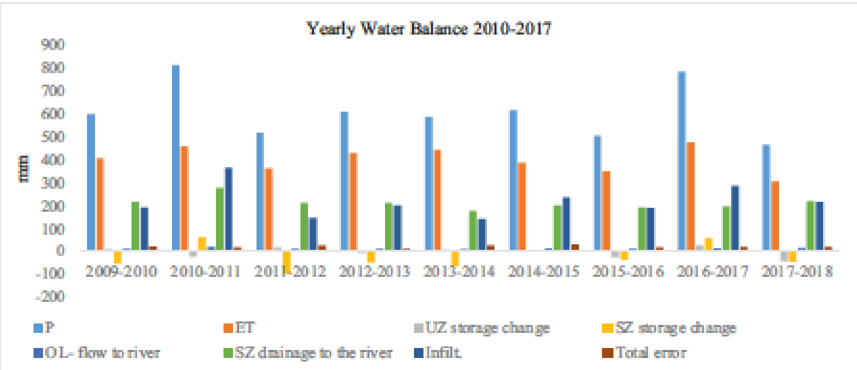


Figure 4.13 Water balance for Tollense river catchment (400 km²) for hydrological years 2010-2017. Negative values of water stored in SZ and UZ shows contribution to the surface water from SZ and UZ respectively and vice versa.

4.4. Discussion

Bi-directional coupled hydrologic and hydraulic model was applied to Tollense river catchment that represents many common features of the European lowland catchments such as shallow GW tables, interacting with SW, control structures, artificial drainage, and periodic inundation etc. Due to these characteristic, modelling described in study offers a huge potential to predict the lowlands response to anthropogenic activities and expected changing climatic conditions and to provide guidelines for management and conservation practices of vulnerable lowland catchments.

4.4.1. Coupled model performance

In general, the coupled model performance in Tollense river catchment was satisfyingly able to describe the interacting hydrologic subsystems GW and SW, assessed by comparison with observed GW levels and SW discharges. Modelling results demonstrate a close association between P, ET, SW discharges and GW levels. Despite the good representation of SW and GW dynamics, coupled model performance was not equally same in all the sub catchments due to heterogeneity of soils and variable availability of field monitoring data. Grid resolution is very important to define the heterogeneity of the catchment according to the desired level of complexity. The finally selected resolution was based on a good compromise between simulation time, numeric robustness and resulted accuracy. But even with a very fine grid it would not feasible to represent small scale variations of geology, which is only exactly known at the borehole locations from the drilling documents. Beside. the required interpolation/generalization of geology, necessary estimates on the exact layout of the artificial drainage and drainage time constants are further uncertainty factors of the GW model. Due to private rights of the farmer's drainage maps were not available during the study, artificial drainage was constructed based on lowest points of DEM in the defined lowland catchment. Calibration process showed that river flows are very responsive to the Manning's n, drainage time constant and leakage coefficients. Water balance estimation during dry and wet years showed the interaction of different water balance components, where ET is a major water loss component and during dry years it reaches up to 65% of total water budget and results in lowering of GW levels due to contribution of GW to SW discharges under minimum GW recharge rates. Coupled model satisfactorily represented the water balance with an error of less than 2% of total water budget.

4.4.2. GW and SW interaction

Coupled model resulted intense interactions among SW and GW. Long term, SW flows follow the pattern of GW levels in the defined catchment with the higher GW flows followed by higher SW discharges. Model calibration of SW discharges was difficult due to the limited monitoring data availability of SW discharges and that highlights the significance of high resolution field monitoring data in hydrological modelling. GW is a major contributor to balance the SW flows during the low flow periods and GW contribution rises up to 45% of total SW flows during observed partial drought in the catchment and with exclusion of river flows from lake Tollense, GW contributes mainly to the Tollense river nearly up to 95% of total SW flows. The simulated hydrograph shows relatively overestimated river flows during peak flow periods. A successful calibration of SZ boundary conditions and geological layers' vertical discretization, saturated hydraulic conductivities, drainage time constant and leakage coefficient play a vital role to successfully quantify the SW and GW interactions. The above discussed differences between simulated and monitored GW levels and SW discharges are due to a combination of different sources of uncertainty: Structural (grid size, simplification of geology), Input data (climate data) and Parameter uncertainty: (e.g. saturated hydraulic conductivity); see also section 3.2 and 3.3.

4.4.3. Key problems associated with coupled hydrological and hydraulic modelling

The advantages of a physical distributed model go along with requiring extensive hydrological input data, high computing capabilities and long computational times and thus increases the overall effort to successfully setup and calibrate the model. Input grid discretization is a priori in MIKE SHE and has to be selected wisely regarding available data, required accuracy and computational effort. Like other hydrological models such as SWAT, MIKE SHE can also simulate catchments size up to thousands of km^2, but for physical distributed models this increases the spatially distributed input data even more than models based on hydrological response units (HRU) do. Like semi distributed models, MIKE SHE cannot represent sub-grid heterogeneity. In case of limited data availability, satellite data can be very helpful for topography and land use estimation but additional terrestrial data acquisition e.g. soil, climatic, aquifer data etc., needs to be gathered. Lack of detailed river cross sections, variation of seasonal Manning's n, drainage maps and leakage coefficient rates impacts the simulated river flows. Limited availability of GW boreholes and monitored GW levels to produce GW contour maps makes it harder to delineate the GW divide and it is sometimes possible to have cross boundary GW flows. Calibration and validation efforts increase enormously in physically distributed models with limited observed data, risking to compensate structural model errors with incorrect model parametrization. Sufficient amount of observed monitoring data will help to provide ease in model setup and during calibration process.

4.4.4. Transfer of methodology to other lowland catchments

Coupled model MIKE SHE and MIKE 11 model has demonstrated its potential to simulate hydrological processes common within lowlands. Extensive data requirements are potential problems to apply coupled physically distributed models in other lowland catchments. Some of the data used in this study is freely available in Germany such as some of the geo-data and climate data provided by DWD (German weather service) platform and can be used for other lowlands in Germany. Manning's n values can be obtained from literature and can be used in other similar catchments. Soil properties were obtained from local environmental protection agency; literature values or field investigations are required for sites with different soil properties. In Europe high resolution DEM model can be obtained from local environmental offices. Lack of detailed river cross sections can be compensated with cross sections based on DEM. Hydraulic structure dimensions can be roughly estimated with Google earth in case of missing information. Calibration of SW discharges and GW flows require monitoring data and there is no other authentic alternative rather than field investigations in the study area.

4.4.5. Key contributions

An integrated hydrological model coupled with a hydrodynamic model was developed with intent to simulate the moderate climate lowland hydrology. In order to represent the surface and subsurface hydrology at a large scale, simplifications and assumptions were made in order to represent the UZ and SZ. Findings support the hypothesis that the hydrological processes in lowlands are dominated by SW and GW interactions. The key contribution of this study includes:

- Development and calibration of a physically-based distributed coupled model to describe the lowlands hydrology, as integrated hydrological–hydraulic modelling has rarely been done in the north-eastern region of Germany;
- The ability of physically-based coupled models to describe the lowland hydrology is demonstrated;
- Simultaneous calibration of SW and GW with a physically-based integrated hydrological model proves the robustness and reliability of an integrated model.
- SW and GW interaction during dry and wet hydrological years in lowlands can be reliably modelled, which is important with regard to the expected and already ongoing change of climatic conditions;
- SW discharges and GW flows can be extrapolated at ungauged sites on a physical basis;
- The method of coupled modelling, including the steps of model setup and calibration can be transferred to other sites with comparable characteristics.

Land use management practices and their results on SW and GW dynamics can be quantified. Further addition of a nutrient transport model is intended and will help to study the SW and GW quality under different land use scenarios

References

1. Jarsjö, J., Asokan, S. M., Prieto, C., Bring, A., & Destouni, G. (2012). Hydrological responses to climate change conditioned by historic alterations of land-use and water-use. *Hydrology and Earth System Sciences, 16*(5), 1335-1347.
2. Nalbantis, I., Efstratiadis, A., Rozos, E., Kopsiafti, M., & Koutsoyiannis, D. (2011). Holistic versus monomeric strategies for hydrological modelling of human-modified hydro systems. *Hydrology and Earth System Sciences, 15*(3), 743-758.
3. Rahim, B. E. E., Yusoff, I., Jafri, A. M., Othman, Z., & Abdul Ghani, A. (2012). Application of MIKE SHE modelling system to set up a detailed water balance computation. *Water and Environment Journal, 26*(4), 490-503.
4. House, AR, Thompson, JR, Sorensen, JPR, Roberts, C., &Acreman, MC (2016). Modelling groundwater / surface water interaction in a managed riparian chalk valley wetland. *Hydrological Processes, 30* (3), 447-462.
5. Graham, DN, & Butts, MB (2005). Flexible, integrated watershed modelling with MIKE SHE. *Watershed models, 849336090*, 245-272.
6. Sandu, M. A., &Virsta, A. (2015). Applicability of mike she to simulate hydrology in Argesel river catchment. *Agriculture and Agricultural Science Procedia, 6*, 517-524.
7. Doppler, T., Honti, M., Zihlmann, U., Weisskopf, P., & Stamm, C. H. (2014). Validating a spatially distributed hydrological model with soil morphology data. *Hydrology and Earth System Sciences, 18*(9), 3481-3498.
8. Kumar, S., Sekhar, M., & Bandyopadhyay, S. (2009). Assimilation of remote sensing and hydrological data using adaptive filtering techniques for watershed modelling. *Current Science*, 1196-1202.
9. Shu, Y., Li, H., & Lei, Y. (2018). Modelling Groundwater Flow with MIKE SHE Using Conventional Climate Data and Satellite Model Data Modelling in Haihe Plain, China. *Water, 10* (10), 1295.
10. Voeckler, HM, Allen, DM, & Alila, Y. (2014). Modelling surface water-groundwater processes in a small mountainous headwater catchment. *Journal of hydrology, 517*, 1089-1106.
11. Hussein, M., & Schwartz, FW (2003). Modelling of flow and contaminant transport in a stream-aquifer system. *Journal of Contaminant Hydrology, 65* (1-2), 41-64.
12. Liang, D., Falconer, RA, & Lin, B. (2007). Coupling surface and subsurface flows in a depth averaged flood wave model. *Journal of Hydrology, 337* (1-2), 147-158.
13. Carroll, RW, Pohll, G., McGraw, D., Garner, C., Knust, A., Boyle, D., &Pohlmann, K. (2010). Mason Valley Groundwater Model: Linking Surface Water and Groundwater

in the Walker River Basin, Nevada 1st *JAWRA Journal of the American Water Resources Association*, *46* (3), 554-573.

14. Goderniaux, P., Brouyère, S., Fowler, H. J., Blenkinsop, S., Therrien, R., Orban, P., &Dassargues, A. (2009). Large scale surface–subsurface hydrological model to assess climate change impacts on groundwater reserves. *Journal of Hydrology*, *373*(1-2), 122-138.
15. Henriksen, HJ, Troldborg, L., Højberg, AL, &Refsgaard, JC (2008). Assessment of exploitable groundwater resource of Denmark by use of ensemble resource indicators and a numerical groundwater surface water model. *Journal of Hydrology*, *348* (1-2), 224-240.
16. Sudicky, E. A., Jones, J. P., Park, Y. J., Brookfield, A. E., &Colautti, D. (2008). Simulating complex flow and transport dynamics in an integrated surface-subsurface modelling framework. *Geosciences Journal*, *12*(2), 107-122.
17. Abbaspour, K. C., Rouholahnejad, E., Vaghefi, S. R. I. N. I. V. A. S. A. N. B., Srinivasan, R., Yang, H., &Kløve, B. (2015). A continental-scale hydrology and water quality model for Europe: Calibration and uncertainty of a high-resolution large-scale SWAT model. *Journal of Hydrology*, *524*, 733-752.
18. Refsgaard, J. C., & Henriksen, H. J. (2004). Modelling guidelines––terminology and guiding principles. *Advances in Water Resources*, *27*(1), 71-82.
19. King, J., Joubert, A., Van Rensburg, L., Rowntree, K., Redelinghuys, N., Esterhuyse, S., ... & Le Roux, P. (2016). MIKE-SHE integrated groundwater and surface water model used to simulate scenario hydrology for input to DRIFT-ARID: theMokolo River case study. *Water SA*, *42*(3),384-398
20. Prucha, B., Graham, D., Watson, M., Avenant, M., Esterhuyse, S., Joubert, A., ... &Rossouw, L. (2016). MIKE-SHE integrated groundwater and surface water model used to simulate scenario hydrology for input to DRIFT-ARID: theMokolo River case study. *Water SA*, *42*(3), 384-398.
21. Munson A D. HSPF modelling of the Charles River Watershed. Dissertation for the Doctoral Degree. Boston: Massachusetts Institute of Technology, 1998.
22. EPA (United States Environmental Protection Agency). Water Quality Modelling Basics and Beyond. EPA Website, available on June 24, 2018.
23. DHI. MIKE SHE User Manual Voume 1: User Guide. Denmark: Danish Hydraulic Institute, 2007.
24. Dhami B S, Pandey A. Comparative review of recently developed hydrologic models. Journal of Indian Water Resources Society, 2013, 33(3): 34–42.

25. Cho Y. Development of a watershed modelling selection program and simple equations as an alternative to complex watershed modelling. Dissertation for the Doctoral Degree. Colorado: Colorado State University, 2013.
26. SloanP G, Moore I D. Modelling surface and subsurface storm flow on steeply-sloping forested watersheds. Water Resources Research, 1984, 20(12): 1815–1822.
27. Duda P B, Hummel P R, Donigian A S Jr, Imhoff J C. BASINS/ HSPF: model use, calibration, and validation. Transactions of the ASABE, 2012, 55(4): 1523–1547.
28. Nasr A E, Bruen M, Jordan P, Moles R, Kiely G, Byrne P. Physically-based, distributed, catchment modelling for estimating sediment and phosphorus loads to rivers and lakes: issues of model complexity, spatial and temporal scales and data requirements. In Paper presented at the National Hydrology Seminar 2004: The Water Framework Directive-Monitoring & Modelling Issues for River Basin Management, November 2004, Tullamore, co. Offaly. Office of Public Works, 2004.
29. Vanderkruk K, Owen K, Grace M, Thompson R. Review of existing nutrient, suspended solid and metal models. Scientific review for Victorian Department of Sustainability and Environment: Aquatic nutrients, suspended solids, pollutant movement and wetland ecology, 2010.
30. Ward G H, Benaman J. Models for TDML application in Texas watercourses: screening and model review. Center for Research inWater Resources, University of Texas at Austin, 1999.
31. Tuo Y, Chiogna G, Disse M. A multi-criteria model selection protocol for practical applications to nutrient transport at the catchment scale. Water, 2015, 7(6): 2851–2880.
32. Kauffeldt A, Wetterhall F, Pappenberger F, Salamon P, Thielen J. Technical review of large-scale hydrological models for implementation in operational flood forecasting schemes on continental level. Environmental Modelling & Software, 2016, 75: 68–76.
33. Al-Khudhairy, DHA, Thompson, JR, Gavin, H., & Hamm, NAS (1999). Hydrological modelling of a draining grazing marsh under agricultural landuse and the simulation of restoration management scenarios. *Hydrological Sciences Journal*, 44 (6), 943-971.
34. Refsgaard, JC, Sørensen, HR, Mucha, I., Rodak, D., Hlavaty, Z., Bansky, L., ... &Enggrob, HG (1998). An integrated model for the Danubian lowland methodology and applications. *Water Resources Management*, *12* (6), 433-465
35. Thompson, J. R. (2012). Modelling the impacts of climate change on upland catchments in southwest Scotland using MIKE SHE and the UKCP09 probabilistic projections. *Hydrology Research*, *43*(4), 507-530.

36. Thompson, JR, Sørenson, HR, Gavin, H., & Refsgaard, A. (2004). Application of the MIKE SHE / MIKE 11 modelling system to a lowland wet grassland in southeast England. *Journal of Hydrology, 293* (1-4), 151-179.
37. Feyen, L., Vázquez, R., Christiaens, K., Sels, O., &Feyen, J. (2000). Application of a distributed-physical hydrological model to a medium size catchment. *Hydrology and Earth System Sciences, 4* (1), 47-63.
38. Huang, Y., Chen, X., Li, Y., Willems, P., & Liu, T. (2010). Integrated modelling system for water resources management of Tarim River Basin. *Environmental Engineering Science, 27*(3), 255-269.
39. Singh, C. R., Thompson, J. R., French, J. R., Kingston, D. G., & Mackay, A. W. (2010). Modelling the impact of prescribed global warming on runoff from headwater catchments of the Irrawaddy River and their implications for the water level regime of Loktak Lake, northeast India. *Hydrology and Earth System Sciences, 14*(9), 1745-1765.
40. Waseem, M., Kachholz, F., & Traenckner, J. (2018). Suitability of common models to estimate hydrology and diffuse water pollution in Northeastern German lowland catchments with intensive agricultural land use. *Frontiers of Agricultural Science and Engineering, 5*(4), 420-431.
41. Monteith, J. L. (1965). Evaporation and environment. In *Symposia of the society for experimental biology* (Vol. 19, pp. 205-234). Cambridge University Press (CUP) Cambridge.
42. Allen, RG, Pereira, LS, Raes, D., & Smith, M. (1998). Crop evapotranspiration guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. *Fao, Rome, 300* (9), D05109.
43. Kristensen, KJ, & Jensen, SE (1975). A model for estimating actual evapotranspiration from potential evapotranspiration. *Hydrology Research, 6* (3), 170-188.
44. Tränckner (Hrsg.) (2018) KOGGE Kommunale Gewässer Gemeinschaftlich Entwickeln - Ein Handlungskonzept für kleine urbane Gewässer am Beispiel der Hanse- und Universitätsstadt Rostock, ISBN 978-3-86009-476-1, online verfügbar unter: https://www.kogge.auf.uni-rostock.de/
45. ATV-DVWK-M 504 (2002): Verdunstung in Bezug zu Landnutzung, Bewuchs und Boden. ATV-DVWK – Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall, früher: Abwassertechnische Vereinigung.
46. Yan, J., & Smith, K. R. (1994). SIMULATION OF INTEGRATED SURFACE WATER AND GROUND WATER SYSTEMS-MODEL FORMULATION 1. *JAWRA Journal of the American Water Resources Association, 30*(5), 879-890.

47. DHI, "Mike She Volume 1: User Guide. The Experts in WATER ENVIRONMENTS," *DHI Softw. Licence Agreem.*, vol. 27, no. 1, pp. 91–95, 2017.
48. Doummar, J., Sauter, M., & Geyer, T. (2012). Simulation of flow processes in a large scale karst system with an integrated catchment model (Mike She)–Identification of relevant parameters influencing spring discharge. *Journal of Hydrology*, *426*, 112-123.
49. Im, S., Kim, H., Kim, C., & Jang, C. (2009). Assessing the impacts of land use changes on watershed hydrology using MIKE SHE. *Environmental geology*, *57*(1), 231.
50. Vázquez, RF, &Feyen, J. (2007). Assessment of the effects of THE gridding on the predictions of basin runoff using MIKE SHE and a modelling resolution of 600 m. *Journal of Hydrology*, *334* (1-2), 73-87.
51. Zhang, Z., Wang, S., Sun, G., McNulty, S. G., Zhang, H., Li, J., ... & Strauss, P. (2008). Evaluation of the MIKE SHE model for application in the Loess Plateau, China 1. *JAWRA Journal of the American Water Resources Association*, *44*(5), 1108-1120.
52. Van Genuchten, M. T. (1980). A closed-form equation for predicting the hydraulic conductivity of unsaturated soils 1. *Soil science society of America journal*, *44*(5), 892-898.
53. Letts, MG, Roulet, NT, Comer, NT, Skarupa, MR, &Verseghy, DL (2000). Parametrization of peat land hydraulic properties for the Canadian Land Surface Scheme. *Atmosphere-Ocean*, *38* (1), 141-160.
54. DHI, 1999. MIKE SHE Water Movement: User manual, Danish Hydraulic Institute, Hørsholm, Denmark
55. Wiek, S., Helm, B., Karrasch, P., Hunger, S., Hoffmann, T. G., Schönrock, S., ... & Mehl, D. Boot-gestütztes längskontinuierliches Monitoring von Fließgewässern mit online-Sonden.

5. Detailed Mass Balance Analysis

Based on the research article:

Waseem, M., Schilling, J., Kachholz, F., & **Tränckner, J.** (2020). Improved Representation of Flow and Water Quality in a North-Eastern German Lowland Catchment by Combining Low-Frequency Monitored Data with Hydrological Modelling.

https://doi.org/10.3390/su12124812

Abstract: Achievements of good chemical and ecological status of groundwater (GW) and surface water (SW) bodies are currently challenged mainly due to poor identification and quantification of pollution sources. A high spatio-temporal hydrological and water quality monitoring of SW and GW bodies is the basis for a reliable assessment of water quality in a catchment. However, high spatio-temporal hydrological and water quality monitoring is expensive, laborious, and hard to accomplish. This study uses spatio-temporally low resolved monitored water quality and river discharge data in combination with integrated hydrological modelling to estimate the governing pollution pathways and identify potential transformation processes. A key task at the regarded lowland river Augraben is (i) to understand the SW and GW interactions by estimating representative GW zones (GWZ) based on simulated GW flow directions and GW quality monitoring stations, (ii) to quantify GW flows to the Augraben River and its tributaries, and (iii) to simulate SW discharges at ungauged locations. Based on simulated GW flows and SW discharges, NO_3-N, NO_2-N, NH_4-N, and P loads are calculated from each defined SW tributary outlet (SWTO) and respective GWZ by using low-frequency monitored SW and GW quality data. The magnitudes of NO_3-N transformations and plant uptake rates are accessed by estimating a NO_3-N balance at the catchment outlet. Based on sensitivity analysis results, Manning's roughness, saturated hydraulic conductivity, and boundary conditions are mainly used for calibration. The water balance results show that 60–65% of total precipitation is lost via evapotranspiration (ET). A total of 85–95% of SW discharge in Augraben River and its tributaries is fed by GW via base flow. SW NO_3-N loads are mainly dependent on GW flows and GW quality. Estimated SW NO_3-N loads at SWTO_Ivenack and SWTO_Lindenberg show that these tributaries are heavily polluted and contribute mainly to the total SW NO_3-N loads at Augraben River catchment outlet (SWO_Gehmkow). SWTO_Hasseldorf contributes least to the total SW NO_3-N loads. SW quality of Augraben River catchment lies, on average, in the category of heavily polluted river with a maximum NO_3-N load of 650 kg/d in 2017. Estimated GW loads in GWZ_Ivenack have contributed approximately 96% of the total GW loads and require maximum water quality improvement efforts to reduce high NO_3-N levels. By focusing on the impacts of NO_3-N reduction measures and best agricultural practices, further studies can enhance the better agricultural and water quality management in the study area.

Keywords: groundwater and surface water interactions; integrated hydrology; lowlands; MIKE SHE; MIKE 11; water management; Water quality

5.1. Introduction

Lowland catchments are characterized by a high groundwater (GW) table, low flow velocity, flat topography, and a significant presence of organic soils [1–4]. In the past centuries, different anthropogenic activities, such as river regulations, enhanced groundwater abstraction, and provision of artificial drainage to ensure better agricultural activities, have caused an impact on ecology, water balance, and nutrient dynamics, resulting in eutrophication and water quality deterioration [5,6]. Diffuse pollution from agriculture has increased considerably over the past few decades due to human activities related to the surplus use of both organic and synthetic fertilizers [7,8]. Over application of nitrogen (N) fertilizers to the crops in thin soils with steeper terrain causes significant damages to the environmental ecosystem, especially during the wet seasons [9]. Surplus nitrogen input is identified as a key contributor to the increased nutrient concentrations in the surface, ground, and coastal waters [10].

In Europe, agricultural activities continue to affect the surface SW and GW quality in terms of NO_3-N pollution [11–13]. The EU nitrate directive was introduced in 1991 to identify and reduce the NO_3-N pollution in water bodies (Directive 91/676/EEC), and it focuses on integrated management of water in river catchments to acquire, improve, or maintain a good chemical and ecological status. Despite enormous efforts, a large ratio of European GW and SW bodies still do not comply with the "good chemical and ecological status" according to the defined criteria of the European water framework directive (EU-WFD). One reason is the still-poor identification, quantification, and management of diffuse pollution sources. The EU-WFD demands to reach a good chemical and ecological status of freshwater bodies by the year 2027. In the case of Germany, improvements are required due to the possible surplus use of agricultural fertilizers. Germany is continuously struggling with GW NO_3-N concentrations higher than 11.3 mg/L, a threshold for a "good chemical and ecological status" of GW [14,15]. Due to deficiencies in implementing the ordinance of agriculture fertilizer application and surplus use of both synthetic and organic fertilizers, a rise in NO_3-N concentrations in comparison to the reported NO_3-N concentrations from 2004 to 2007 is observed [16,17]. In 2016, the European court of justice brought legal action against Germany due to deficiencies in implementing the ordinance of agriculture fertilizer applications [7,18].

The whole situation stresses the more effective measures needed to understand and reduce diffuse NO_3-N emissions, transport, and transformation processes, especially for lowlands with intensive agricultural activities. This demands high spatio-temporal hydrological and water quality monitoring at a catchment and regional scale. Normally, high-resolution monitoring data in most of the lowland catchments are not available to reliably quantify and access the chemical and ecological status of water bodies and to identify critical areas and/or hidden point sources requiring the maximum measures to reduce the SW and GW NO_3-N concentrations. A detailed water and mass balance information is essential to develop and improve the management practices of water resources, as SW and GW interactions mainly control the NO_3-N dynamics in lowland rivers [19]. Physically based hydrological models can quantify the GW and SW interactions, and can simulate GW flow directions and SW discharges at ungauged locations. Hydrological modelling results, in combination with low-frequency monitored water quality data, can estimate the SW and GW NO_3-N pollution loads at catchment and sub-catchment scales. To select a suitable modelling tool to simulate Augraben catchment (a typical representative of north-eastern Germany lowland catchments), four different process-based models, "SWAT" (soil and water assessment tool), "SWIM" (soil and water integrated model), "HSPF" (hydrological simulation program—FORTRAN), and a coupled "MIKE SHE and MIKE 11" model, are reviewed. These models are compared by concentrating primarily on temperate-climate lowland catchments with intensive agricultural land use. Appendix A shows the summary of reviewed models based on simulated hydrological and hydraulic processes, governing equations, input data requirements, spatial and temporal discretization, and limitations [20–31]. The physically based distributed coupled MIKE SHE and MIKE 11 model is selected in this study to quantify the detailed water balance, simulation of surface flows at ungauged locations, and interactions of GW and SW at a desired level of complexity.

This study uses available low-frequency monitored flow and water quality data in combination with integrated hydrological and hydraulic modelling to represent the SW and GW hydrology and NO_3-N loads in Augraben River catchment. The research objectives of the present study include: (i) Detailed water balance estimation and quantification of GW and SW interactions, (ii) application of simulated SW discharges at ungauged locations to calculate NO_3-N loads at each SW tributary outlet (SWTO), (iii) estimation of the saturated zone represented by each GW quality monitoring station and quantification of GW contribution to the SW NO_3-N loads, (iv) identification of critical areas and sources mainly contributing to the water quality deterioration, and (v) estimation of a nutrient balance at Augraben River catchment outlet to evaluate the magnitude of NO_3-N transformations and plant uptakes.

5.2. Material and Methods

5.2.1. Study Area

Augraben River is the largest tributary of the Tollense River in terms of discharge and length. It is located in the lowlands of north-eastern Germany and is representative for the typical lowland flood plains of Central Europe. The Augraben River has a total length of 18 km up to the gauge station Gehmkow. The area of the Augraben River catchment up to the gauge station Gehmkow is 90 km^2. In the study area, the precipitation normally happens throughout the year in Augraben River catchment, with the most precipitation during the 31 days centred around July. The least precipitation normally occurs around February. On average, the temperature normally varies from −1 to 25 °C, and is rarely below –8 °C or above 31 °C during the course of the year. The wet season lasts from May to February, with more than 24% chance of a given day being a wet day. The drier season lasts from February to May (https://weatherspark.com/ and https://dwd.de). **Figure 5.1** (a) shows the average monthly temperature and precipitation in the study area during 2017. The topography is very flat in the study area. The lowest points at the Augraben River bed level vary between 40 (u/s) and 28 m (d/s) above NN (Reference Level).

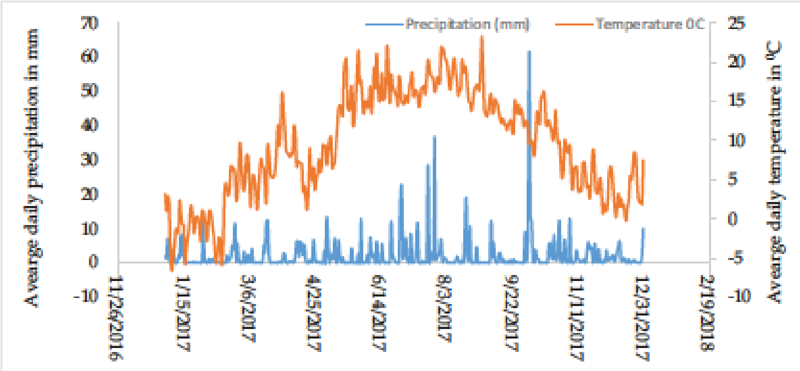
The main tributaries of Augraben River include Lindenberg, Hasseldorf, and Au II Kentzlin. Three wastewater treatment plants (WWTPs) are located within the Augraben River catchment: WWTP_Lindenburg, WWTP_Ivenack, and WWTP_Stavenhagen. The treated wastewater is discharged into the Augraben River and its tributaries, and then finally flows to the Tollense River. **Table 5.1** characterizes the WWTP in terms of populations equivalents (PE) calculated from their inflow loads of chemical oxygen demand (COD), total nitrogen (N), and total phosphorus (P). Additionally, to the domestic wastewater, WWTP_Stavenhagen handles the wastewater from a large potato processing company and shows, therefore, a very high COD load. The nutrient loads are, in comparison, much smaller. The is in the German size class 5, and has fulfilled emission standards of N-inorganic: 13 mg/L and P: 1 mg/L [32]. The rural WWTPs of Lindenberg (activated sludge system) and Ivenack (pond system) are treating less than 1000 PE.

The Augraben River is still considered heavily loaded with nutrients. In Augraben River catchment, agricultural activities and concentrated animal feeding operations are assumed to be contributing most to the diffuse GW NO_3-N pollution. For the implementation of the Nitrates Directive, Germany has formulated a nationwide action programme for the reduction of nitrate applications. Important elements of the Fertilizer Ordinance include the application of permitted amounts of fertilizer during the allowed time periods with a minimum distance to be maintained from the SW bodies. The Revision of the German Fertilizer Ordinance in 2017 specifies only an upper limit for animal manure application, and a farm should, on average, apply less than 170 kg nitrogen per hectare per annum [33].

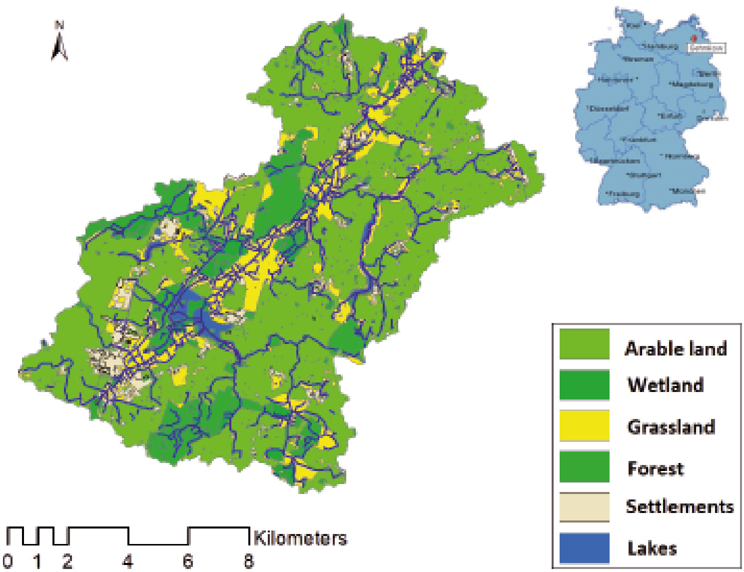
Table 5.1 Population equivalent of all three wastewater treatment plants' (WWTPs') inflow chemical oxygen demand (COD), total nitrogen (N), and total phosphorus (P).

	Standard Emissions	**WWTP Lindenberg**		**WWTP Ivenack**		**WWTP Stavenhagen**	
	Kg/d-inhabitant	kg/d	PE	kg/d	PE	kg/d	PE
COD	0.12	11.60	96.72	75.90	632.52	12510.22	104251.9
N	0.011	1.68674	153.34	4.09	371.86	654.280	59480
P	0.0018	0.19	107.22	0.9951	552.8	88.304	49058.18

Due to the increased NO_3-N concentrations, the Augraben River catchment is characterized by high primary production of weeds in the vegetation period and the formation of organic sediments. Land use in Augraben River catchment is mainly agricultural. The geology is very heterogeneous and consists mainly of glacial deposits of fluvial sand and glacial till. Due to extreme geological heterogeneity, a large and diverse system of unconfined and confined aquifers with dissimilar flow directions and residence times exists in the lowlands located in north-eastern Germany. The land-use classification in Augraben catchment, shown in **Figure 5.1** (b), consists of 2% settlements, 2.22% water, 75% arable and grassland, 18% forest area, and 3% miscellaneous. The study area is highly regulated for improved agricultural activities.



(a)



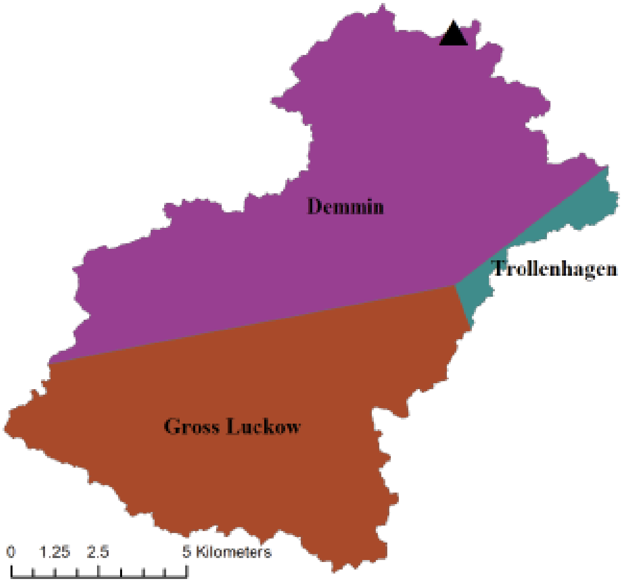
(b)

Figure 5.1 (**a**) Average daily precipitation and temperature in the study area in 2017. (**b**) Land use in Augraben River catchment. Land-use, rivers, and lakes data are provided by "Landesamt für Umwelt, Naturschutz und Geologie Mecklenburg Vorpommern (LUNG-MV)" ©.

5.2.2. Data Collection

5.2.2.1. Climate data

Climate data were collected as accumulated daily rainfall at three climate monitoring stations named Demmin, Gross-Luckow, and Trollenhagen. Demmin is located within the catchment, while Gross-Luckow and Trollenhagen are located nearby but outside the study area. The representative area of each climate station was calculated by the Thiessen Polygon method of interpolation, as shown in **Figure 5.2**. The Penman–Monteith method was used to calculate the potential evapotranspiration in the study.



(a)

Figure 5.2 Representative catchment area of each climate monitoring station estimated by the Thiessen Polygon interpolation method.

5.2.2.2. Land-use

Land use is based on Rapid Eye Archive images (https://resa.blackbridge.com). Land-use classification was performed to classify the land use into arable land, forest, grassland, wetland, lakes, and settlement areas. Average root depths (RD) for different land-use classifications during the winter and summer season are shown in **Table 5.2**. Leaf area index (LAI) in monthly resolution is presented in **Figure 5.3**. RD and LAI were collected from the project KOGGE (www.kogge.auf.uni-rostock.de) conducted in a nearby catchment by University of Rostock.

Table 5.2 Average root depths (RD) for different land-use classes during winter and summer season in Augraben River catchment [34].

Land-use	Average Root Depth in Winter (mm)	Average Root Depth in Summer (mm)
Arable land	200	600
Wetlands	300	300
Grassland	100	300
Forest	800	800
Settlements	600	600
Water surfaces	0	0

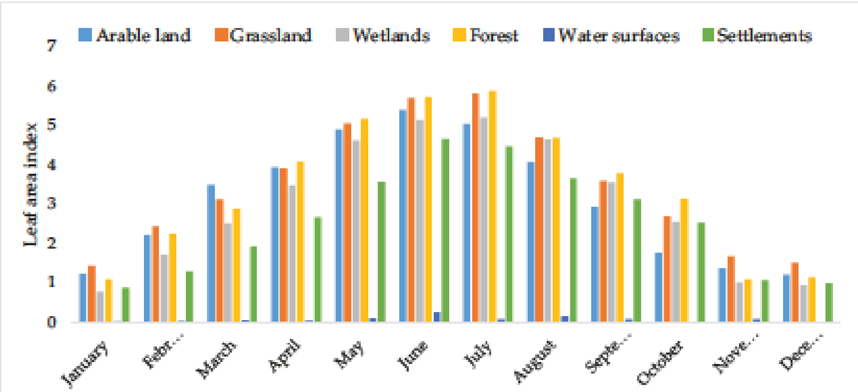


Figure 5.3 Leaf area index (LAI) average monthly variation in Augraben River catchment [34].

5.2.2.3. Surface water discharge data

SW flow data at discharge monitoring station Gehmkow were collected from the local environmental protection department (StÄLU-MS) in average daily resolution for a period ranging from 2010 to 2018. Surface flow monitoring station Gehmkow is regarded as Augraben River catchment's outlet and it summarizes all of the upstream monitoring. No surface flow data were available at other independent tributaries (Lindenberg, Hasseldorf, and Ivenack) contributing to the Augraben River. **Figure 5.4** describes the location of the discharge monitoring station and the main tributaries and their outlets in the Augraben River catchment. The collected observed flow data were used later for flow calibration in hydrological modelling.

5.2.2.4. Water quality and WWTP effluent data

The locations of available GW and SW quality monitoring stations in the Augraben River catchment are shown in Figure 4. GW quality data were only available for the GW monitoring stations (GWMSs) named GWMS_Törpin and GWMS_Genevzow, and were obtained from StÄLU-MS in yearly resolution. For this study, additional GW samples were collected at three selected GW monitoring stations (GWMS) named GWMS_Lindenberg, GWMS_Hasseldorf, and GWMS_Ivenack at monthly resolution from January 2017 to December 2017. These water samples were analysed for NO_3-N, NO_2-N, and NH_4-N concentrations. To monitor the GW level, five boreholes were installed at GWMS_Genevzow, GWMS_Lindenberg, GWMS_Ivenack, GWMS_Törpin, and GWMS_Hasseldorf. The GW data loggers provided data with hourly resolution starting from November 2016 to April 2018. Monitored GW levels were used for calibration and validation of the coupled hydrological and hydrodynamic model.

SW monitoring was performed by StÄLU-MS for NO_3-N, NO_2-N, NH_4-N, and P concentrations at the green marked outflows of sub-catchments. The data are available at monthly resolution, but without the according flow data. Effluent flow volume and NO_3-N and total P concentrations from three WWTPs (WWTP_Ivenack, WWTP, Stavenhagen, and WWTP_Lindenberg) located in the study area were obtained also from StÄLU-MS. SW quality classification was performed by using the German surface water ordinance [36]. The surface water ordinance specifies water quality classes from I (unpolluted) to IV (excessively contaminated).

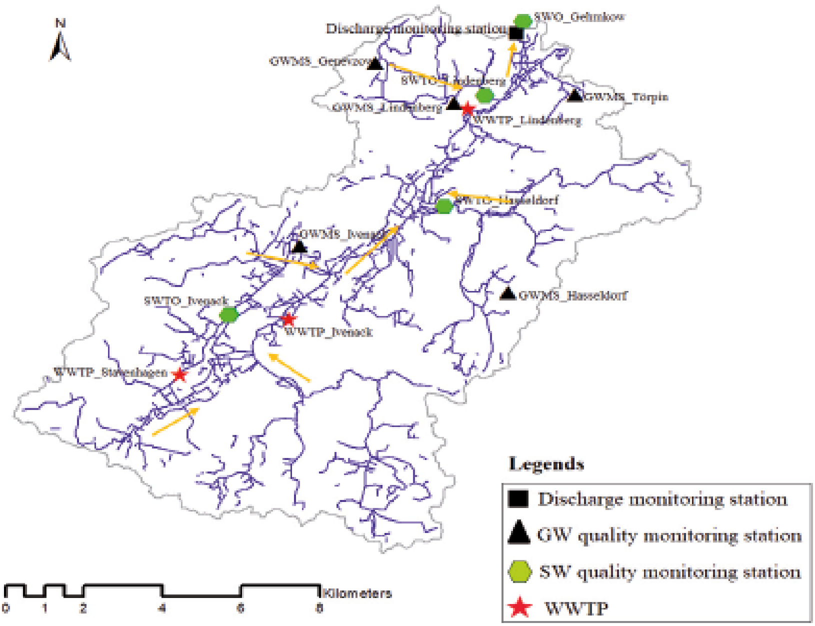


Figure 5.4 . Location of WWTPs, surface water flow directions (yellow arrows), surface discharge, groundwater quality, and surface water quality monitoring stations in Augraben River catchment © LUNG-MV.

5.2.3. MIKE SHE Process-Based Modelling and Mass Balance Framework

As discussed above, MIKE SHE was chosen because of its ability to model GW and SW interactions and dynamics within a catchment in a physical and reliable way [36,37]. The modelling framework describing hydrological processes at the desired level of complexity and spatio-temporal variability used in this study is explained in **Figure 5.5**. The digital elevation model (DEM) is used as a data development function to define the catchment boundary and stream network. Spatial disaggregation in MIKE SHE is represented by square grids, and the catchment is distributed into grids of equal size. Each square grid is considered homogeneous. Grid-based formulation of MIKE SHE is compatible with grid-based satellite and weather radar data. The soil column is sectioned into three layers: (i) Surface layer, (ii) soil layer, and (iii) groundwater layer in the MIKE SHE model to simulate GW and SW interactions and flows. The MIKE SHE process-based modelling framework includes spatial lumping approaches on catchment and sub-catchment levels. Finally, a hydrodynamic model 11 is coupled with the integrated hydrological model MIKE SHE. MIKE 11 can simulate hydraulic structures. The model framework was also chosen to facilitate the later incorporation of transformation processes using Ecolab. Based on the resulting detailed water balance and simulated SW discharges, SW and GW dynamics and SW and GW NO_3-N loads are estimated [38–40].

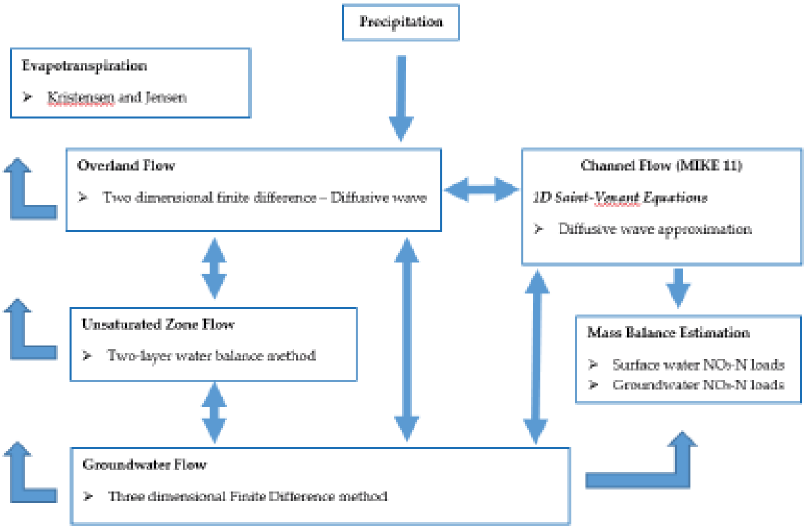
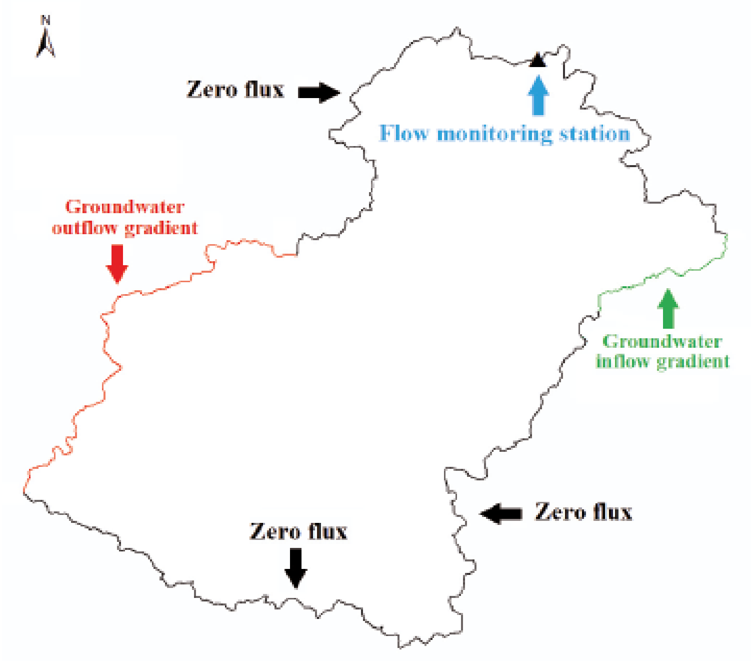
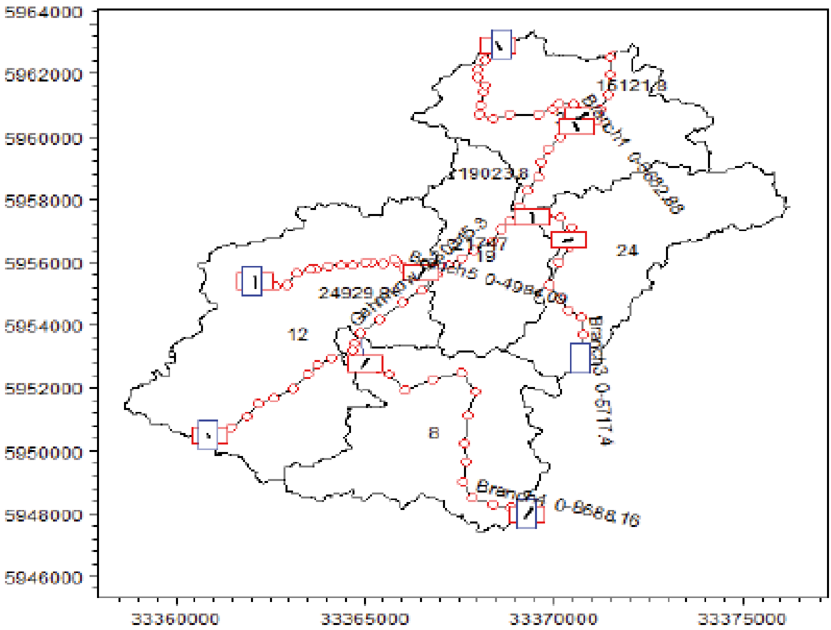


Figure 5.5 . Schematic of the modelling framework used in this study.

The hydrological cycle in MIKE SHE is described by a water movement module (WMM). The WMM of MIKE SHE includes precipitation/interception, evapotranspiration (ET), overland (OL) flow, unsaturated zones (UZ), saturated zones (SZ), and exchange between GW and SW. The ET in MIKE SHE is estimated by using the Kristensen–Jensen method. The flow in UZs is modelled by using a two-layer water balance method. SZ flows in MIKE SHE are simulated by using 3D Boussinesq equation. Simplified diffusive wave approximation of the Saint-Venant equation is used to simulate the river hydrodynamics. The coordinate system "ETRS_1989_UTM_Zone_33N_8stellen", in metric units, is used in this study. Based on the computational time and resulting model performance, the catchment area is divided into 50 × 50 m grids. The topography in the study area is represented by a digital elevation model (DEM) at 5 m resolution and was provided by StÄLU-MS. Zero-flux and GW inflow and outflow gradients are used as aquifer boundary conditions (BC), as shown in **Figure 5.6** (a). Catchment boundaries where lateral flows were likely to be negligible based on GW contours are defined as zero-flux BC. However, catchment boundaries where GW lateral inflow and outflow were expected are defined as positive and negative GW gradient BC. The geology is based on borehole log data and is mainly represented by three geological layers in the SZ of Augraben River catchment. The borehole log data from the available 23 boreholes in the study area were used to define the aquifer depth. The river network containing the Augraben River and its tributaries is defined in MIKE 11, as shown in **Figure 5.6** (b). The coupling of MIKE SHE and MIKE 11 was done dynamically by considering the exchange of data between river links in MIKE 11 to the adjacent MIKE SHE grids after every computational time step [41].



(a)



(b)

Figure 5.6 (a) Boundary conditions used in the saturated zone, where black line is zero flux boundary condition, the green line is inflow groundwater gradient boundary condition, and the red line is outflow groundwater gradient boundary condition; (b) Augraben River and its tributaries simulated in this study.

5.3. Results

5.3.1. Coupled Hydrological and Hydraulic Model Calibration and Validation

The most sensitive parameters for the Augraben River catchment were assessed by sensitivity analysis. Sensitivity analyses were performed by adjusting one parameter value at a time, while keeping others constant in a particular simulation; the magnitude of impact on the simulated results was evaluated for every single parameter value adjustment/change. The resulting most sensitive parameters include initial potential heads, BCs, and saturated hydraulic conductivity. Hourly monitored GW levels

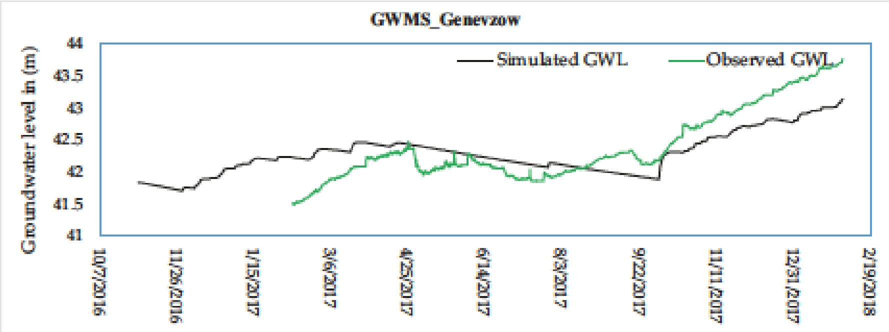
(November 2016–April 2018) at GWMS_Genevzow, GWMS_Lindenberg, and GWMS_Ivenack were used for the calibration of simulated GW levels. GW levels at GWMS_Törpin and GWMS_Hasseldorf from January 2011 to December 2015 were used for model validation. After model calibration and validation, the coupled MIKE SHE and MIKE 11 model was used for generating discharges at ungauged locations. **Table 5.3** describes the calibration parameters, initial and calibration value ranges, selected calibrated values, and statistical performance of GW and SW calibration and validation. Simulated and observed GW levels and SW discharges are shown in **Figure 5.7** (a), (b), respectively. Coupled hydrological and hydraulic model performance was evaluated by using mean absolute error (MAE), Nash-Sutcliffe efficiency (NSE), correlation coefficient (R), and standard deviation residuals (STDres).

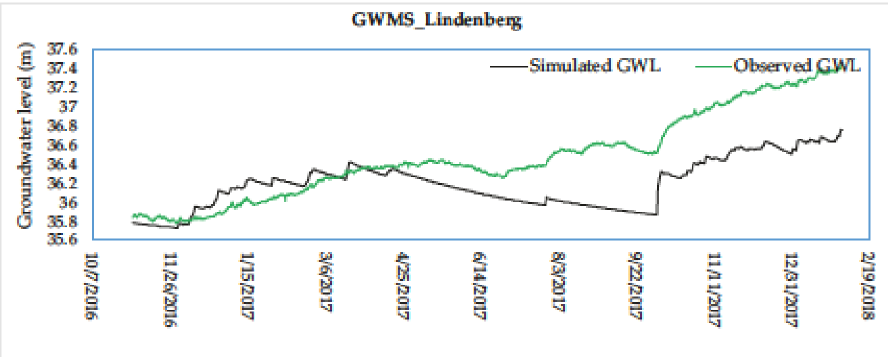
Table 5.3 Calibration parameters, their ranges, final values, and statistical performance of the coupled model.

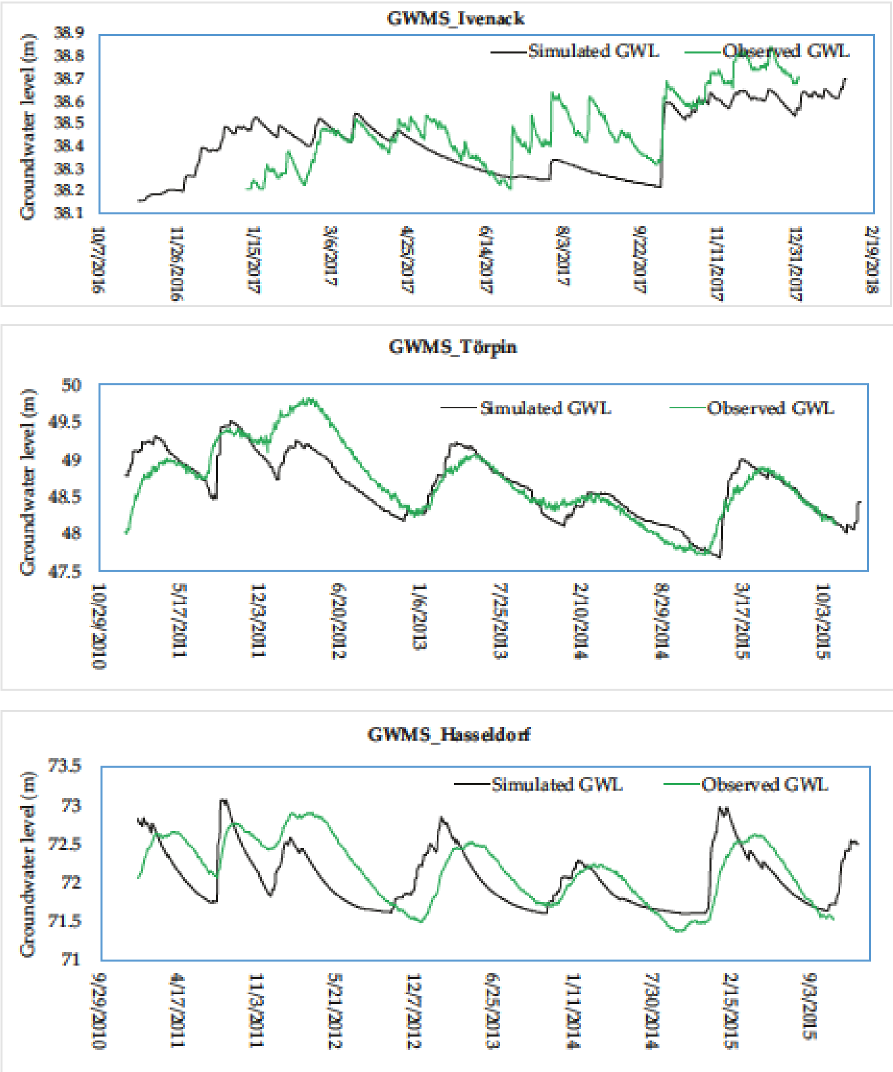
<table>
<tr><th colspan="5">Calibration Process</th></tr>
<tr><th>Selected Parameters</th><th colspan="2">Initial Input Value</th><th>Input Range</th><th>Calibrated Value</th></tr>
<tr><td>Hydraulic conductivity [m/s]</td><td colspan="2">A: 1×10^{-6}
B: 1×10^{-8}
C: 1×10^{-10}</td><td>1×10^{-10}–1×10^{10}
1×10^{-10}–1×10^{10}
1×10^{-10}–1×10^{10}</td><td>1×10^{-4}
1×10^{-7}
1×10^{-10}</td></tr>
<tr><td>Specific yield</td><td colspan="2">A: 0.25
B: 0.2
C: 0.1</td><td>1×10^{-10}–1×10^{10}
1×10^{-10}–1×10^{10}
1×10^{-10}–1×10^{10}</td><td>0.266
0.20
0.108</td></tr>
<tr><td>Boundary condition Groundwater inflow and outflow gradients</td><td colspan="2">+ve gradients: 0.0015
−ve gradients: 0.004</td><td>0.009–−0.009
0.009–−0.009</td><td>0.0036
−0.004</td></tr>
<tr><td>Manning roughness coefficient</td><td colspan="2">Natural channel: 10
Weirs or concrete surfaces: 80</td><td>10–25
80–100</td><td>15
85</td></tr>
<tr><th colspan="5">Statistical performance of groundwater calibration</th></tr>
<tr><th>Monitoring Station</th><th>MAE (m)</th><th>NSE</th><th>R (Correlation)</th><th>STDres</th></tr>
<tr><td>GWMS_Genevzow</td><td>1.467</td><td>0.60</td><td>0.845</td><td>0.352</td></tr>
<tr><td>GWMS_Ivenack</td><td>1.159</td><td>0.63</td><td>0.749</td><td>0.131</td></tr>
</table>

GWMS_Lindenberg	0.478	0.61	0.786	0.351
Statistical performance of groundwater validation				
GWMS_Hasseldorf	1.09	0.65	0.7403	0.24
GWMS_Törpin	1.500	0.67	0.646	0.411
Statistical performance of river flow calibration				
Monitoring Station	**MAE (m^3/s)**	**NSE**	**R (Correlation)**	**STDres**
SWO_Gehmkow	0.4514	0.31	0.7797	0.5299

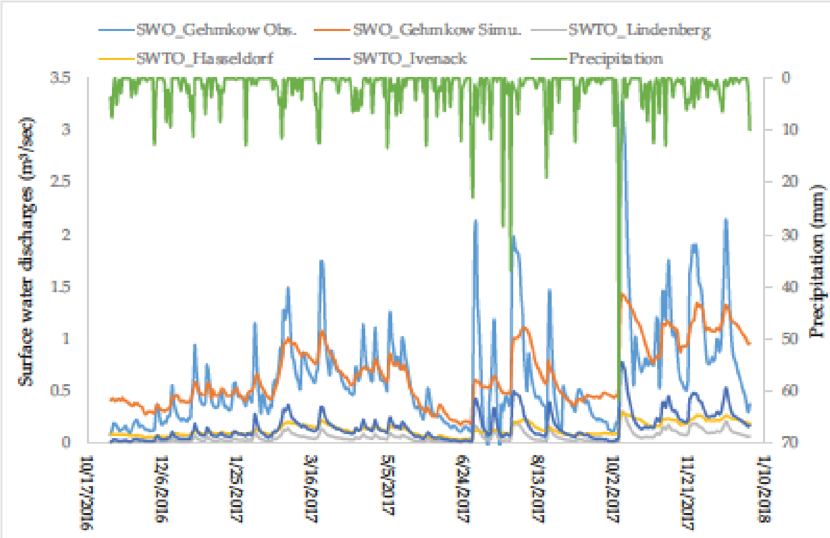
MAE = "mean absolute error in meter"; NSE = "Nash-Sutcliffe efficiency"; R = "Correlation"; STD = "Standard deviation residuals"






GWMS_Ivenack
Groundwater level (m)
38.9
38.8
38.7
38.6
38.5
38.4
38.3
38.2
38.1
Simulated GWL
Observed GWL
10/7/2016
11/26/2016
1/15/2017
3/6/2017
4/25/2017
6/14/2017
8/3/2017
9/22/2017
11/11/2017
12/31/2017
2/19/2018
GWMS_Törpin
Groundwater level (m)
50
49.5
49
48.5
48
47.5
Simulated GWL
Observed GWL
10/29/2010
5/17/2011
12/3/2011
6/20/2012
1/6/2013
7/25/2013
2/10/2014
8/29/2014
3/17/2015
10/3/2015
GWMS_Hasseldorf
Groundwater level (m)
73.5
73
72.5
72
71.5
71
Simulated GWL
Observed GWL
9/29/2010
4/17/2011
11/3/2011
5/21/2012
12/7/2012
6/25/2013
1/11/2014
7/30/2014
2/15/2015
9/3/2015

(a)



(b)

Figure 5.7 Observed and Simulated groundwater levels (a), and observed and simulated surface water discharges (b) in the study area.

The simulated results show that GW levels are high during the winter and low during the summer season due to respective low and high ET rates. In the current study, the coupled MIKE SHE and MIKE 11 model underestimated the GW levels during high recharge periods. However, model performance was not equally comparable at all monitoring locations, but showed a strong spatio-temporal relationship between simulated GW levels and observed climatic data (precipitation, ET). First, we compare the flow with the only available monitoring station in Gehmkow. Here, the volume balance is met well, while the dynamics are underestimated during high flows and overestimated during low flows with an R^2 (Nash Sutcliff) of −0.873687. This possibly happens due to the provision of artificially constructed drainage in MIKE SHE based on the lowest DEM points. The constructed drainage does not fully reflect the installed drainage in the Augraben River catchment; Figure 1 shows the branched drainage system used in this study. Drainage becomes ineffective when the GW levels fall below the provided artificial drainage levels in MIKE SHE, resulting in smaller GW contribution to the Augraben River and its tributaries. Afterwards, the calibrated model was applied to calculate flows at the ungauged locations.

5.3.2. Water Balance Estimation

A detailed yearly water balance was performed for the Augraben River catchment for 2010–2018. Each hydrological year was considered from 1 October to 30 September of the upcoming year based on local conditions. In this study, the hydrological model gets its total water input via precipitation and SZ GW inflow. The total water budget was further divided into ET, surface runoff, change in UZ and SZ storage, and GW and SW interactions. Water balance error was estimated based on total inflows (precipitation, surface and subsurface GW inflow), outflows (ET, overland flow, surface and subsurface GW outflow, GW and SW interactions), and change in UZ and SZ storage. The water balance error of 2% during the calibration period shows the suitable model performance during the simulation period of 2010–2018. Detailed water balance results show that ET loss represents an approximate average of 60–65% of the total precipitation in the study area. The GW contribution to the Augraben River and its tributaries as a base flow and the SW contribution to the GW as infiltration and percolation show the exchange of flows between MIKE SHE and MIKE 11. SW discharge is mainly fed by GW. The GW contribution to total SW discharges accounts for up to 85–95%. The water balance results show a small decrease in SZ storage over the period of the last eight hydrological years. **Table 5.4** shows the detailed water balance for the Augraben River catchment; all values are in millimetres (mm). Positive and negative storage change represents the ascending and descending change in water stored in SZ and UZ.

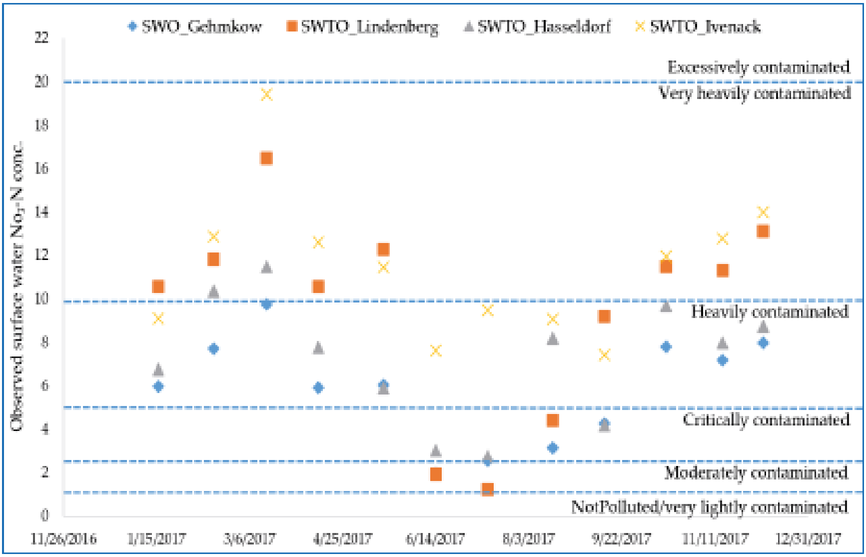
Table 5.4 Water balance for Augraben catchment (90 km²) during hydrological year 2010-2018, all values are in millimeters (mm).

Water balance components (mm)	2010 – 2011	2011 – 2012	2012 – 2013	2013 – 2014	2014 – 2015	2015 – 2016	2016 – 2017	2017 – 2018	2010 – 2018
Precipitation	804	511	597	573	599	502	767	447	4814
Evapotranspiration	473	376	445	456	401	367	482	316	3324
Canopy storage change	0	0	0	0	0	0	0	0	0

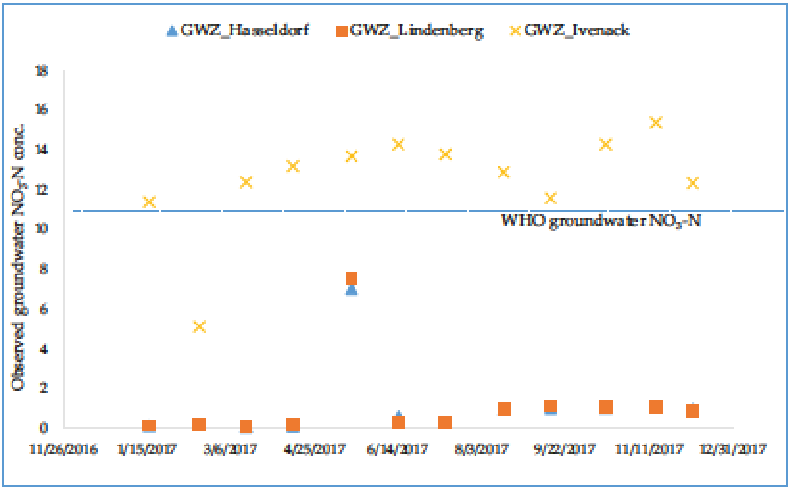
Overland flow to the river	59	38	37	26	35	34	37	44	311
Snow storage change	0	0	0	0	0	0	0	0	0
Overland storage change	8	-2	-4	2	1	0	6	-7	5
UZ storage change	−24	20	−6	6	1	−26	29	−44	−42
SZ storage change	22	−146	−80	−95	−21	−50	39	−53	−388
SZ drain to river	123	90	79	62	68	66	68	79	638
Infiltration	373	138	182	124	213	180	264	204	1681
Exfiltration	88	61	58	42	54	53	52	68	477
UZ boundary inflow	0	0	0	0	0	0	0	0	0
UZ boundary outflow	3	1	1	1	1	1	2	2	13
SZ boundary inflow	61	55	50	43	43	42	38	43	377
SZ boundary outflow	202	187	175	159	155	152	143	152	1330

5.3.3. Surface Water and Groundwater Quality

Observed SW and GW quality data in Augraben River catchment were partially measured (at officially existing monitoring locations) and partially obtained from the local environmental protection department in Augraben River catchment. Observed SW and GW NO_3-N concentrations were distributed into pollution classes according to the federal surface water ordinance [35] and the World Health Organization's (WHO) [15] guidelines for NO_3-N in GW, respectively. In terms of SW quality, 35.41% of the collected SW samples showed NO_3-N concentrations belonging to the category of very heavily contaminated rivers. A total of 43.75% of the SW samples fell under the category of heavily contaminated and 6.25% moderately contaminated. None of the SW samples showed concentrations belonging to the category of lightly or non-polluted rivers. Observed NO_3-N concentrations and their respective pollution categories are shown in **Figure 5.8**. Classification at the tributary scale shows that measured NO_3-N concentrations at the tributary outlets named SWTO_Lindenberg and SWTO_Ivenack come under the water quality class of very heavily polluted, as the measured NO_3-N concentrations are clearly elevated, and concentration is reduced only in months from June to September, but still lies in the category of heavily polluted rivers. For approximately similar land-use conditions in the study area, low SW NO_3-N concentrations were observed at SWTO_Hasseldorf. This shows that the SWTO_Lindenberg and SWTO_Ivenack water quality monitoring stations were possibly influenced by the point sources contributing to SW pollution. The observed SW NH_4-N concentrations also lie in the category of very highly contaminated rivers. In terms of GW NO_3-N concentrations, 30% of the GW samples collected in the study area in 2017 showed higher concentrations then the threshold limit defined by the WHO for GW. GW quality classification shows that the GW zone (GWZ) Ivenack NO_3-N concentrations throughout the year are higher than the threshold value of 11.3 mg/L defined by the WHO. However, GWZ_Lindenberg and GWZ_Hasseldorf show lower NO_3-N concentrations.



(a)



(b)

Figure 5.8 Classification of Augraben River and its tributaries surface water (a) and groundwater quality (b) based on oberflächengewässer verordnung [35].

ET follows the intensity of incoming solar radiation and the resulting number of sunshine hours during the course of the year. Low ET in combination with moderate precipitation during the winter and spring seasons results in higher discharges. Fertilizer is applied primarily in spring and (to a lower extent) in early autumn, and plant nitrogen uptake follows the pattern of ET in the study area. Total monthly NO_3-N loads at SWO_Gehmkow follow the seasonal pattern of the total monthly runoff volume. GW quality monitoring is influenced by various factors. Observed NO_3-N concentrations at a particular GWMS do not wholly represent the water quality status of a GWZ. The reliability of GW monitoring is influenced by the selection and location of the boreholes [42,43]. In the study area, qualitative monitoring was performed at two hydrological boreholes bi-yearly and at three boreholes monthly. MIKE SHE coupled with a hydrodynamic model MIKE 11 simulated the GW levels and flow directions in the study area. In order to quantify the representative area of the saturated zone under each monitored borehole, the calibrated GW model MIKE SHE coupled with a hydrodynamic model MIKE 11 was applied to estimate GW flow directions. The constructed GW contours explain that the GW flow direction is towards the Augraben River and its tributaries throughout the catchment, and that underlines that GW largely contributes to the surface discharges. However, GWZ_Ivenack is special, as GW contributes to the tributary and also passes underneath the river towards lower GW elevations. The GW table, in general, follows the topography of the catchment; however, in some areas, it differs from the topography. Water in the saturated zone flows due to differences in the energy state of the water, described by the term hydraulic head. The GW flow is determined by the gradient in the hydraulic head and the hydraulic conductivity, which is an empirical constant describing the ability of geological media to transmit water. Based on GW flow directions and available GW monitoring stations in the study area, the representative area was estimated according to each available GW quality monitoring station. The Augraben River catchment is divided into three GWZs (GWZ_Lindenberg, GWZ_Hasseldorf, and GWZ_Ivenack), as shown in **Figure 5.9**. The boreholes named GWMS_Genevzow and GWMS_Lindenberg are located in GWZ_Lindenberg, boreholes GWMS_Törpin and GWMS_Hasseldorf are located in GWZ_Hasseldorf, and GWMS_Ivenack is located in the GWZ_Ivenack. GW flow paths vary greatly in length and depth depending on where the GW recharges and the travel time within a catchment. In highly polluted areas, it is necessary to conduct reliable monitoring of GW, as better GW quality assessment will help in counteracting the negative effects of pollution [44–47].

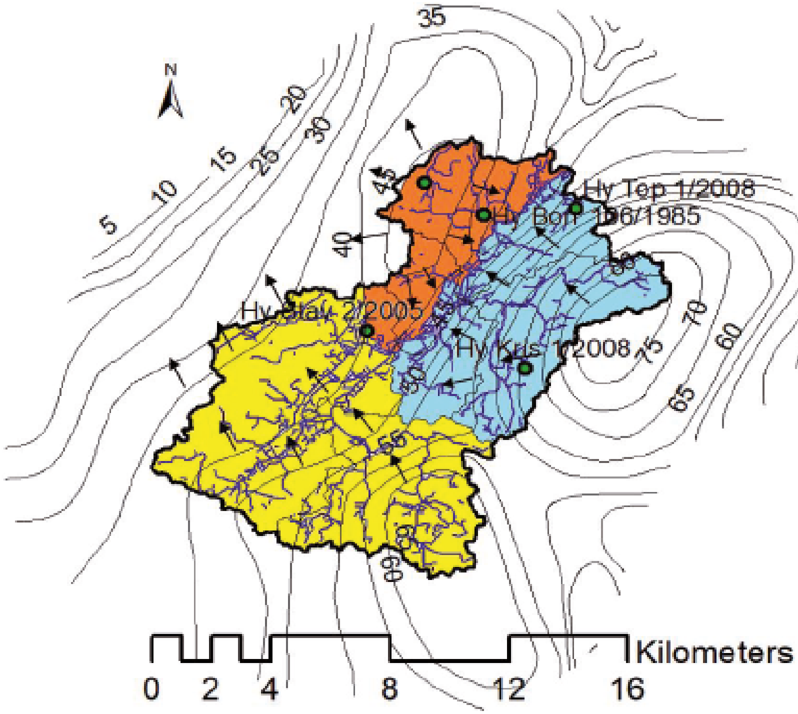


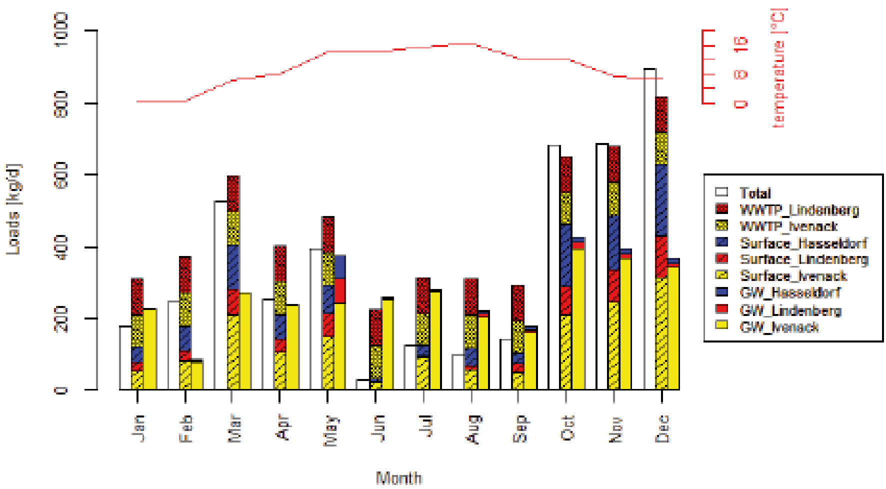
Figure 5.9 Based on simulated groundwater contours and flow directions defined sub-catchments possibly represented by each available groundwater quality monitoring station; GWZ_Lindenberg (red), GWZ_Hasseldorf (blue), and GWZ_Ivenack (yellow).

5.3.4. Nutrient Balance at Catchment Outlet

The uncertainties in average concentration and load estimations can be reduced by increasing the sampling frequency. However, the SW and GW sampling, sample transport, and laboratory procedures are expensive and laborious. A favourable approach is the load estimation from available observed low-frequency concentration data. The explanatory strength of commonly available continuous measurements, such as precipitation, discharge, and GW levels at limited locations, in combination with hydrological modelling can access water quality variation at ungauged locations. Most of the commonly available hydrological measurements (precipitation, temperature, wind speed, etc.) are relatively inexpensive and often available near SW and GW quality monitoring locations to facilitate the quantitative management of water. First, simulated SW discharges obtained from the coupled MIKE SHE and MIKE 11 model were used to estimate the SW NO_3-N, NO_2-N, NH_4-N, and total P loads at SWTO_Lindenberg, SWTO_Hasseldorf, SWTO_Ivenack, and SWO_Gehmkow. WWTPs and their effluent NO_3- N and total P loads were added to estimate the NO_3-N balance and NO_3-N transformations at the Augraben River outlet. Secondly, simulated GW flows for each respective GWZ were used to calculate the GW NO_3-N loads in all three GWZs, named as GWZ_Lindenberg (red), GWZ_Hasseldorf (blue), and GWZ_Ivenack (yellow). It is estimated that GWZ_Lindenberg and GWZ_Hasseldorf contribute the least to the GW NO^3-N loads, while GWZ_Ivenack, based on measured concentrations and GW volumes, contributes a maximum of up to 96% in terms of GW NO_3-N loads. The possible causes behind the higher observed GW NO_3-N concentrations at GWZ_Ivenack in comparison to GW NO_3-N concentrations at GWZ_Lindenberg and GWZ_Hasseldorf include (1) infiltration from two nearby WWTPs, where WWTP_ stavenhagen is a large-scale WWTP, and effluent NO_3-N load discharged into the tributary Ivenack can infiltrate into the GW. As NO_3-N loads are detectable at SWTO_Ivenack, that is why WWTP NO_3-N loads are not specified separately in **Figure 5.10** (a). Total effluent NO_3-N loads from WWTP_Stavenhagen account for 47.84 kg/d. Direct GW infiltration is negligible or zero, as WWTP_Stavenhagen does not allow GW infiltration due to its construction and operational design. WWTP_Ivenack is a pond-type WWTP and can possibly influence the GW quality due to infiltration. However, its small-scale operational capacity also limits its possible contribution to GW quality. Stormwater runoff from biogas plants and other agricultural facilities was identified in other studies as a potentially relevant pollution source [48]. As the land use type is nearly the same in the Augraben River catchment, higher GW concentration could also point to a different fertilizer usage behaviour in different areas of the catchment. A high spatio-temporal monitoring is necessary to evaluate the GW and SW quality variation at a smaller scale, but it is evident from the estimated GW loads that the highest GW loads occur in June, July, August, and September.

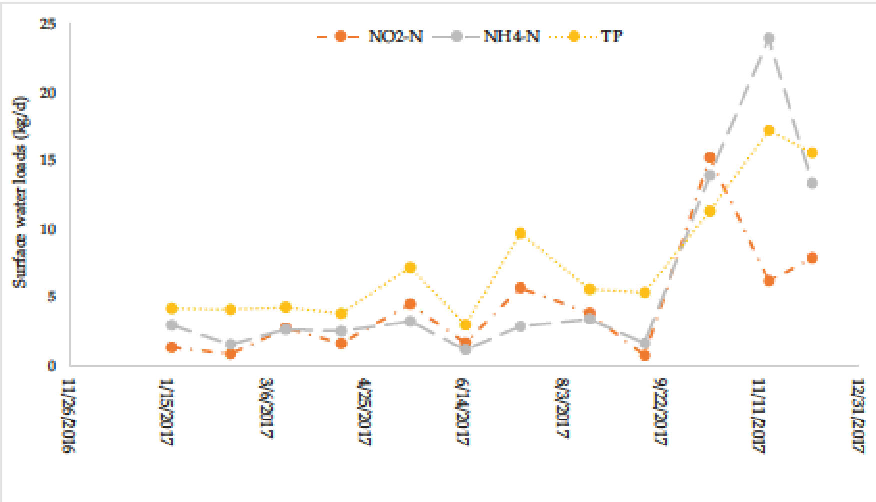
The nutrient balance of the estimated SW loads at the Augraben River outlet is shown in Figure 10a. It reveals that, especially in summer, the total NO_3-N loads at SWO_Gehmkow are lower than the sum of the calculated SWTO_Lindenberg, SWTO_Hasseldorf, SWTO_Ivenack, and WWTP effluent loads. Here, an inverse relationship between NO_3- N loads and observed water temperature is visible. The higher reduction in SW NO_3- N loads at the outlet during the summer months indicates significant transformation either by denitrification or by increased plant growth. In winter or during times with low water temperatures, the biological processes are reduced to a very low level while base flow increases, resulting in higher nitrate loads. The difference between total SW loads at SWO_Gehmkow and the summed loads from SWTO_Lindenberg, SWTO_Hasseldorf, SWTO_Ivenack, and WWTP gives the magnitude of the transformation and plant uptake, on average, of up to 50% of total loads at SWO_Gehmkow during the months of June, July, August, and September. The loads of NO_2-N, NH_4-N, and total P are shown in **Figure 5.10** (b). In general, SWO_Gehmkow's water quality status lies in the strongly polluted river category.

The main findings of nutrient balance at SWO_Gehmkow include (1) estimation of SW and GW loads from each SWTO and representative GWZ; (2) estimation of NO_3-N transformation and plant uptake rate; (3) critical SW and GWZ identifications requiring maximum measures to reduce NO_3- N loads; (4) explanation of possible NO_3-N hotspots influencing the water quality. It is recommended that the locations of water quality monitoring stations should be reconsidered based on tributaries with heavy pollution and GW flow directions to accurately point out the hotspots. This study highlights the need for further necessary measures to achieve the EU-WFD goals and demands a stronger process-oriented monitoring. A valuable improvement would already be flow measurement in parallel with grab sampling.



Loads [kg/d]
temperature [°C]
Total
WWTP_Lindenberg
WWTP_Ivenack
Surface_Hasseldorf
Surface_Lindenberg
Surface_Ivenack
GW_Hasseldorf
GW_Lindenberg
GW_Ivenack
Month

(a)



NO2-N
NH4-N
TP
Surface water loads (kg/d)

(b)

Figure 5.10 (**a**) Surface water tributary outlet (SWTO), WWTP, and groundwater zone (GWZ) NO_3-N loads in the Augraben River catchment and their relation with water temperature; (**b**) calculated NO_2-N, NH_4-N, and total P loads at the Augraben River outlet.

5.4. Discussion

The bi-directional coupled hydrologic (MIKE SHE) and hydraulic (MIKE 11) model was applied to the Augraben River catchment, a tributary of the Tollense River. The Augraben River catchment represents common features of the European lowland catchments, such as shallow GW tables, GW and SW interactions, control structures, provision of artificial drainage, periodic inundation, etc. Due to these features, the modelling approach explained in the current study has a huge potential to simulate/predict the lowland response to anthropogenic activities and expected changing climatic conditions and to provide guidelines for better conservation and management practices of susceptible catchments.

5.4.1. Method Strengths

5.4.1.1. Water Balance

Water balance estimation in a river catchment predicts the detailed SW and GW interactions. A detailed water balance explains the main water loss components and will help in developing watershed management practices and better informed policy decisions [49,50]. In this study, the calibrated coupled MIKE SHE and MIKE 11 model has predicted the water balance with an error of less than 2%. ET is a main water loss component. Surface discharges are mainly fed by GW, and GW flow is a dominant pathway in the Augraben River catchment. Higher GW contributions to SW discharges in lowland Augraben River catchment are following the hydrological studies conducted in lowland catchments in north-eastern Germany [1,51–53]. Overland flow or direct runoff is very low in comparison to other water balance components. Lowland catchments are characterized with low direct runoff flows in contrast to mountainous catchments, where direct SW runoff is a dominant pathway [54,55]. The resulting GW contribution to surface GW and SW interactions mainly controls the pollutant (NO_3-N) dynamics and influences the SW and GW quality [56,57].

5.4.1.2. Simulated Surface Flow at Ungauged Locations and Groundwater Levels

The lack of SW discharge monitoring stations in small or remote catchments is a hurdle in defining the catchment management measures [58,59]. In the Augraben River catchment located in north-eastern Germany, discharge data were only available at the catchment outlet. No measured discharges were available at the Augraben River's tributaries. In the current study, the GW levels and surface discharges were successfully generated by the integrated coupled hydrological and hydraulic model (MIKE SHE and MIKE 11). The simulated discharge at Gehmkow shows good agreement between simulated and observed discharge with an R (correlation) of 0.7797 and RMSE of 0.579. The performance of the calibrated model is not the same at all locations due to the defined simplifications during the modelling procedure.

5.4.1.3. Mass Balance and NO_3-N Transformation Rates

The NO_3-N pollution of SW and GW is a major environmental problem, especially in lowlands with intensive agriculture and related farm activities. Achievement of environmental sustainability requires the detailed assessment of spatial and temporal variation of water quality at the catchment and regional scale. River mass balance methods using observed or simulated flows and pollutant concentrations can be helpful in describing the magnitude and extent of existing pollutant loads along a river [60,61]. Based on coupled hydrological and hydraulic model results, we have successfully estimated the NO_3-N loads at the catchment and sub-catchment scale by combining low-frequency monitoring data with hydrological modelling. GW levels were available at only two monitoring stations. In terms of water quality assessment and its variations at a catchment scale, limited monitoring data were available. This enhances both the explanatory strength of generally available and inexpensive quantitative hydrological data and the (so far, only) qualitative status information from grab sampling [62]. The responses of NO_3-N and P concentrations can be plausibly linked to the hydrological dynamics of SW and GW, triggered by the meteorological input. Combining these data with measured emission data of WWTP, a trustworthy source apportionment between diffuse and known point sources is feasible. In summertime, the measured load is lower than the predicted sum. The difference can be a rough estimate of NO_3-N transformations and plant uptake rates. The results of this study demonstrate, in line with similar studies [63,64], that using the explanatory strength of quantitative hydrological data can significantly improve load estimates.

5.4.2. Method Weakness

Short-term dynamics of SW quality variations are not captured by common low-frequency grab sampling. The low-frequency monitoring provides an overview of the average concentrations of chemical species and suggests some general processes that may explain the observed data. The added value of high-frequency monitoring is the possibility of capturing diurnal cycles and transient events that help relate the causes and effects of human activities and storms. High-frequency monitoring can go much further in the interpretation of the data and can more precisely uncover and/or confirm rapid processes at work in the system [65–67]. The method can reliably estimate the contribution of diffuse sources. To explain loads from point sources, additional data are needed. Here, only the data of WWTP emissions could be included. Polluted storm water runoff could be an additional nutrient input, which was not addressed so far.

From the qualitative perspective, the method is purely data-driven. It could be considered to expand the hydrological model by additional transformation processes. This was out of the scope of this study, aiming at an improved interpretation of available monitoring data. However, with regard to designing mitigation measures, an expanded process model would be worthwhile.

5.4.3. Transfer of Methodology to Other Lowland Catchments

The method of the applied coupled hydrological model in combination with low-frequency monitored data can be transferred at the desired rate of complexity to similar lowland catchments. According to our assessment, the chosen model setup was best suited to simulate the typical characteristics of lowland catchments, such as (i) artificial drainage to support better agriculture activities, (ii) backwater effect due to smaller slopes, (iii) complex SW and GW interactions, and (iv) river flows. The subsequent mass balance and source apportionment are valuable to prioritize and allocate measures to reduce nutrient emissions.

However, the method is not delimited to the model framework chosen here. Under different boundary conditions, other models could be equally or even more advisable. Four different process-based models—"soil and water assessment tool" (SWAT), "soil and water integrated model" (SWIM), "hydrological simulation program—FORTRAN" (HSPF), and a coupled "MIKE SHE and MIKE 11" model—were compared in this study. The DHI's combined tools and SWAT were more suitable for simulating the desired hydrological processes, but in the case of river hydraulics, the integrated coupling between MIKE SHE and MIKE 11 is a plus. In the case of SWAT, it needs to be coupled with another tool to model the hydraulics in the Augraben River, as SWAT does not simulate the backwater effects and operation of control structures (weirs, gates, etc.). However, both the SWAT and DHI tools are more data-demanding in comparison to SWIM and HSPF. HSPF, in turn, already contains tools to model nitrogen transformation and transport processes along the hydrological system, which is helpful for designing mitigation measures. Most of the input data and governing equations in the case of SWIM and SWAT are similar. SWIM does not simulate water bodies (ponds and lakes), wetlands, and drainage systems.

5.4.4. Usefulness of Model Predictions and Future Applications

The analysis of the model's predictions/future forecasts and deficiencies related to model structure and availability of data offers better understanding of the processes (water and nutrient) at different temporal (monthly and annual) and spatial scales (catchment, sub-catchment, river). In the Augraben River catchment, critical areas were identified where in-depth additional investigations are required. In particular, the specific emissions in the Ivenack sub-catchment were noticeably higher than in the other sub-catchments. Accordingly, monitoring and systems analysis should be strengthened here to support better catchment management practices/activities. As expected, higher NO_3-N loads occur outside the vegetation period during autumn and winter. Estimated NO_3-N loads are heavily influenced by temperature. The differences between forecasted and measured nitrate loads in SW can be interpreted/transformed/removed; loads are very low during the winter and autumn seasons due to the lower temperatures. Environmental conditions during the summer and spring seasons favour higher plant uptake and increased microbial activities.

5.4.5. Key Parameters to Reduce Nitrogen Inputs

The study was performed in the phase when the new fertilizer regulation came into effect. The observed state still represents the conditions before the stronger regulations. It can be assumed that the reduced tolerated nitrogen surplus will, in the longer term, be viable in reduced nitrogen concentrations at the GW, and will accordingly reduce loads to the SW. The increased specific loads from the Ivenack catchment may not only be due to farming activities. For several years, polluted storm water runoff from sealed areas on animal farms and biogas plants has been suspected to be an important nutrient point source. In addition, the view should be open to so far unidentified polluters. Regular water quality monitoring and sampling frequency at a higher resolution will help in reliable and precise assessment of the status of surface and groundwater bodies.

5.5. Conclusion

The NO_3-N pollution of SW and GW is a major environmental problem, especially in lowlands with intensive agriculture and related farm activities. Achievement of environmental sustainability requires the detailed assessment of spatial and temporal variation of water quality at the catchment and regional scale. The required high-resolution spatial and temporal monitoring for profound assessment is often in contrast the existing data. This study, conducted in a north-eastern German lowland catchment, aims at improving the expressiveness of inconsistent monitoring data by combining it with a coupled hydrologic model. The main conclusions are:

- By combining a coupled SW/GW model with spatially and temporally scarce grab samples, the dominant nutrient entry pathways can be roughly allocated and quantified.
- Process-based hydrological modelling can help in defining SW and GW quality monitoring locations and schedules.
- The modelling approach can be transferred to similar lowlands, and a calibrated coupled model can be used to identify the priority areas to reduce nutrient pollution. Differences between accumulated loads and measured total loads can be used as rough estimates for instream transformation processes.

The SW quality in the investigated Augraben River system varies—applying national and international assessment schemes—between moderately to very heavily polluted. Total load reached a maximum NO_3-N load of 650 kg/d in 2017. In the summer season, GW loads' contribution is higher in comparison to the total load at the catchment outlet. However, in winter, a higher SW load is calculated with a small increase in GW load. NO_3-N loads from point sources, such as WWTP, cannot be neglected. In this study, estimated GW loads in GWZ_Ivenack contributed the most to the total GW loads. WWTP_Stavenhagen, on average, contributes 25% of the total NO_3-N load at SWTO_Ivenack. Areas with higher NO_3-N loads (GWZ_Ivenack in this study) require maximum water quality improvement efforts to reduce high NO_3-N levels.

References

1. Lam, Q.D.; Schmalz, B.; Fohrer, N. Assessing the spatial and temporal variations of water quality in lowland areas, Northern Germany. *J. Hydrol.* **2012**, *438*, 137–147.
2. Schmalz, B.; Springer, P.; Fohrer, N. Variability of water quality in a riparian wetland with interacting shallow groundwater and surface water. *J. Plant. Nutr. Soil Sci.* **2009**, *172*, 757–768.
3. Krause, S.; Bronstert, A.; Zehe, E. Groundwater–surface water interactions in a North German lowland floodplain–implications for the river discharge dynamics and riparian water balance. *J. Hydrol.* **2007**, *347*, 404–417.

4. Hesse, C.; Krysanova, V.; Päzolt, J.; Hattermann, F.F. Eco-hydrological modelling in a highly regulated lowland catchment to find measures for improving water quality. *Ecol. Model.* **2008**, *218*, 135–148.
5. Sophocleous, M. Interactions between groundwater and surface water: The state of the science. *Hydrogeol. J.* **2002**, *10*, 52–67.
6. Kieckbusch, J.J.; Joachim S. Nitrogen and phosphorus dynamics of a re-wetted shallow-flooded peatland. *Sci. Total Environ.* **2007**, *380*, 3–12.
7. Kirschke, S.; Häger, A.; Kirschke, D.; Völker, J. Agricultural Nitrogen Pollution of Freshwater in Germany. The Governance of Sustaining a Complex Problem. *Water* **2019**, *11*, 2450.
8. de Wit, M.; Behrendt, H.; Bendoricchio, G.; Bleuten, W.; van Gaans, P. The contribution of agriculture to nutrient pollution in three European rivers, with reference to the European Nitrates Directive. *Eur. Water Manag. Online* **2002**, 1-19.
9. Zhang, W.; Li, H.; Kendall, A.D.; Hyndman, D.W.; Diao, Y.; Geng, J.; Pang, J. Nitrogen transport and retention in a headwater catchment with dense distributions of lowland ponds. *Sci. Total Environ.* **2019**, *683*, 37–48.
10. Heathwaite, L.; Sharpley, A.; Gburek, W. A conceptual approach for integrating phosphorus and nitrogen management at watershed scales. *J. Environ. Qual.* **2000**, *29*, 158–166.
11. Hildebrandt, A.; Guillamón, M.; Lacorte, S.; Tauler, R.; Barceló, D. Impact of pesticides used in agriculture and vineyards to surface and groundwater quality (North Spain). *Water Res.* **2008**, *42*, 3315–3326.
12. Schoumans, O.F.; Chardon, W.J.; Bechmann, M.E.; Gascuel-Odoux, C.; Hofman, G.; Kronvang, B.; Dorioz, J. M. Mitigation options to reduce phosphorus losses from the agricultural sector and improve surface water quality: A review. *Sci. Total Environ.* **2014**, *468*, 1255–1266.
13. Böhlke, J.K. Groundwater recharge and agricultural contamination. *Hydrogeol. J.* **2002**, *10*, 153–179.
14. He, B.; Kanae, S.; Oki, T.; Hirabayashi, Y.; Yamashiki, Y.; Takara, K. Assessment of global nitrogen pollution in rivers using an integrated biogeochemical modelling framework. *Water Res.* **2011**, *45*, 2573–2586.
15. Xue, Y.; Song, J.; Zhang, Y.; Kong, F.; Wen, M.; Zhang, G. Nitrate pollution and preliminary source identification of surface water in a semi-arid river basin, using isotopic and hydrochemical approaches. *Water* **2016**, *8*, 328.

16. COMMISSION STAFF WORKING DOCUMENT EXECUTIVE SUMMARY OF THE IMPACT ASSESSMENT Accompanying the Document PROPOSAL for a REGULATION of the European Parliament and of the Council Laying down Rules on the Making Available on the Market of CE Marked Fertilising Products and Amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52016SC0065 (accessed on 20 May 2020).
17. Directive, N. *Nitrate Pollution in the Groundwater Resources of the Public Drinking Water Supply*. Water Solutions, 70048 Stuttgart, 2017; pp. 25–35.
18. Härtel, J. *Das EuGH-Urteil vom 21. Juni 2018 zum Versto Gegen die EU-Nitratrichtlinie Durch die Bundesrepublik Deutsch-Land: Seine Relevanz für die Richtlinienkonformität des Neuen Düngerechts*; Rechtsgutachten Erstellt im Auftrag des Verbands Kommunaler Unternehmen e.V.: Europa-Universität Viadrina Frankfurt, 2018. Availabe online: https://www.vku.de/fileadmin/user_upload/Verbandsseite/Themen/Umwelt/21_10_2018_Prof_Dr_Ines_Haertel_Gutachten_EuGH_Urteil_Nitratrichtlinie.pdf (accessed on 10 May 2020).
19. Winter, T.C. Relation of streams, lakes, and wetlands to groundwater flow systems. *Hydrogeol. J.* **1999**, *7*, 28–45.
20. Jiang, S.; Michael R. Hydrological Water Quality Modelling of Nested Meso Scale Catchments. Ph.D. Thesis. Technische Universität Braunschweig, 38106 Braunschweig, 2014.
21. Dhami, B.S.; Pandey, A. Comparative review of recently developed hydrologic models. *J. Indian Water Resour. Soc.* **2013**, *33*, 34–41.
22. Gao, L.; Li, D. A review of hydrological/water-quality models. *Front. Agric. Sci. Eng.* **2014**, *1*, 267–276.
23. Benaman, J.; Shoemaker, C.A.; Haith, D.A. Calibration and validation of soil and water assessment tool on an agricultural watershed in upstate New York. *J. Hydrol. Eng.* **2005**, *10*, 363–374.
24. Shoemaker, L.; Dai, T.; Koenig, J.; Hantush, M. *TMDL Model Evaluation and Research Needs*; Cincinnati OH: National Risk Management Research Laboratory: US Environmental Protection Agency, Cincinnati, Ohio 45268, 2005.
25. Fehér, J.; Muerth, M. *Water Models and Scenarios Inventory for the Danube Region*; Report EUR 27357EN, European Commission Joint Research Centre Institute for Environment and Sustainability, Luxembourg, 2015. Availabe online: https://core.ac.uk/download/pdf/38630655.pdf (accessed on 10 April 2020).

26. Ward, G.H.; Jennifer B. *A Survey and Review of Modelling for TMDL Application in Texas Watercourses*; Center for Research in Water Resources, University of Texas: Austin, TX, USA, 1999.
27. Kauffeldt, A.; Wetterhall, F.; Pappenberger, F.; Salamon, P.; Thielen, J. Technical review of large-scale hydrological models for implementation in operational flood forecasting schemes on continental level. *Environ. Model. Softw.* **2016**, *75*, 68–76.
28. Chen, Y.; Li, W.; Fang, G.; Li, Z. Hydrological modelling in glacierized catchments of central Asia-status and challenges. *Hydrol. Earth Syst. Sci.* **2017**, *21*
29. Krysanova, V.; Fred, H.; Rank, W. Development of the ecohydrological model SWIM for regional impact studies and vulnerability assessment. *Hydrol. Process. Int. J.* **2005**, *19*, 763–783.
30. Waseem, M.; Kachholz, F.; Klehr, W.; Tränckner, J. Suitability of a Coupled Hydrologic and Hydraulic Model to Simulate Surface Water and Groundwater Hydrology in a Typical North-Eastern Germany Lowland Catchment. *Appl. Sci.* **2020**, *10*, 1281.
31. Waseem, M.; Frauke K.; Jens T. Suitability of common models to estimate hydrology and diffuse water pollution in North-eastern German lowland catchments with intensive agricultural land use. *Front. Agric. Sci. Eng.* **2018**, *5*, 420–431.
32. Jardin, N. Vereinheitlichung und Herleitung von Bemessungswerten für Abwasseranlagen (A 198). In Proceedings of the Regen-und Mischwasserbehandlung Seminar, Würzburg, Technische Akademie Hannover, Germany, 23–24 September 2003.
33. Kuhn, T. *The Revision of the German Fertiliser Ordinance in 2017*; No. 1548-2017-3861; Institute for Food and Resource Economics, University Bonn, Nussallee 21, 53155 Bonn, Germany, 2017.
34. Tränckner, H. *KOGGE Kommunale Gewässer Gemeinschaftlich Entwickeln-Ein Handlungskonzept für Kleine Urbane GEWÄSSER am Beispiel der Hanse- und Universitätsstadt Rostock*; Universität Rostock: Rostock, Germany, 2018.
35. Verordnung zum Schutz der Oberflächengewässer (Oberflächengewässerverordnung; OGewV) vom 20. Juni 2016. In: BGBI., 2016, I, S. 1 373). Available online: https://www.gesetze-im-internet.de/ogewv_2016/OGewV.pdf (accessed on 3 May 2020).
36. Thompson, J.R. Modelling the impacts of climate change on upland catchments in southwest Scotland using MIKE SHE and the UKCP09 probabilistic projections. *Hydrol. Res.* **2012**, *43*, 507–530.

37. Singh, C.R.; Thompson, J.R.; French, J.R.; Kingston, D.G.; Mackay, A.W. Modelling the impact of prescribed global warming on runoff from headwater catchments of the Irrawaddy River and their implications for the water level regime of Loktak Lake, northeast India. *Hydrol. Earth Syst. Sci*. **2010**, *14*, 1745–1765.
38. Butts, M.B.; Overgaard, J.; Graham, D.; Dubicki, A.; Strońska, K.; Szalinksa, W.; Larsen, O. Process-based Hydrological Modelling Framework MIKE SHE for Flood Forecasting on the Upper and Middle Odra. In Proceedings of the ICID 21st European Regional Conference, Frankfurt (Oder), Germany; Slubice, Poland, 15–19 May 2005.
39. Thai, T.H.; Tri, D.Q. Combination of hydrologic and hydraulic modelling on flood and inundation warning: Case study at Tra Khuc-Ve River basin in Vietnam. *Vietnam J. Earth Sci.* **2019**, *41*, 240–251.
40. Altaf, Y.; Manzoor A.; Mohammad F. Modelling snowmelt runoff in Lidder River Basin using coupled model. *Int. J. River Basin Manag.*, vol. 18, no. 2, pp. 167-175, 2020.
41. Ivanescu, V.; Radu D. Deriving Rain Threshold for Early Warning Based on a Coupled Hydrological-Hydraulic Model. *Math. Model. Civ. Eng*. **2016**, *12*, 10–21.
42. Hosseini, M.; Reza K. A data fusion-based methodology for optimal redesign of groundwater monitoring networks. *J. Hydrol.* **2017**, *552*, 267–282.
43. Gomo, M.; Vermeulen, D.; Lourens, P. Groundwater sampling: Flow-through bailer passive method versus conventional purge method. *Nat. Resour. Res*. **2018**, *27*, 51–65.
44. Grath, J.; Scheidleder, A.; Uhlig, S.; Weber, K.; Kralik, M.; Keimel, T.; Gruber, D. *The EU Water Framework Directive: Statistical Aspects of the Identification of Groundwater Pollution Trends, and Aggregation of Monitoring Results*; Final Report; Austrian Federal Ministry of Agriculture and Forestry, Environment and Water Management, Vienna, 2001.
45. Jousma, G.; Roelofsen, F.J. *World-Wide Inventory on Groundwater Monitoring*. Report nr. GP1; International Groundwater Resources Assessment Center, 2611 AX Delft, Netherlands, 2004.
46. Nielsen, D.M.; Gillian N. *The Essential Handbook of Ground-Water Sampling*; CRC Press, Taylor and Francis Group, 6000 Boca Raton, 2006.
47. Quevauviller, P.; Fouillac, A.M.; Grath, J.; Ward, R. *Groundwater Monitoring*; Water Quality Measurements Series; Willey: New York, NY, USA, 2009; p. 428.
48. Cramer, M.; Rinas, M.; Kotzbauer, U.; Tränckner, J. Surface contamination of impervious areas on biogas plants and conclusions for an improved stormwater management. *J. Clean. Prod.* **2019**, *217*, 1–11.

49. Yapiyev, V.; Skrzypek, G.; Verhoef, A.; Macdonald, D.; Sagintayev, Z. Between boreal Siberia and arid Central Asia–Stable isotope hydrology and water budget of Burabay National Nature Park ecotone (Northern Kazakhstan). *J. Hydrol. Reg. Stud.* **2020**, *27*, 100644.
50. Yapiyev, V.; Skrzypek, G.; Verhoef, A.; Macdonald, D.; Sagintayev, Z. A proportionality-based multi-scale catchment water balance model and its global verification. *J. Hydrol.* **2020**, *582*, 124446.
51. Smith, A.; Tetzlaff, D.; Gelbrecht, J.; Kleine, L.; Soulsby, C. Riparian wetland rehabilitation and beaver re-colonization impacts on hydrological processes and water quality in a lowland agricultural catchment. *Sci. Total Environ.* **2020**, *699*, 134302.
52. Waseem, M.; Tatyana K.; Jens T. Groundwater Contribution to Surface Water Contamination in a North German Low Land Catchment with Intensive Agricultural Land Use. *J. Water Resour. Prot.* **2018**, *10*, 231.
53. Lam, Q.D.; Britta, S.; Nicola F. The impact of agricultural Best Management Practices on water quality in a North German lowland catchment. *Environ. Monit. Assess.* **2011**, *183*, 351–379.
54. Van Griensven, A.; Meixner, T.; Grundwald, S.; Bishop, T.; Diluzio, A.; Srinivasan, R. A global sensitivity analysis tool for the parameters of multi-variable catchment models. *J. Hydrol.* **2006**, *324*, 10–23.
55. Lenhart, T.; Eckhardt, K.; Fohrer, N.; Frede, H.-G. Comparison of Two Different Approaches of Sensitivity Analysis. *Physics and Chemistry of the Earth; Parts A/B/C*, Volume 27, 2002, pp. 645–654.
56. Dahm, C. N.; Grimm, N. B.; Marmonier, P.; Valett, H. M.; Vervier, P. Nutrient dynamics at the interface between surface waters and groundwaters. *Freshw. Biol.* **1998**, *40*, 427–451.
57. van Geer, F.C.; Kronvang, B.; Broers, H.P. High-resolution monitoring of nutrients in groundwater and surface waters: Process understanding, quantification of loads and concentrations, and management applications. *Hydrol. Earth Syst. Sci.* **2016**, *20*, 3619.
58. Jia, P.; Liu, R.; Ma, M.; Liu, Q.; Wang, Y.; Zhai, X.; Wang, D. Flash Flood Simulation for Ungauged Catchments Based on the Distributed Hydrological Model. *Water* **2019**, *11*, 76.
59. Chouaib, W.; Alila, Y.; Caldwell, P. V. On the use of mean monthly runoff to predict the flow–duration curve in ungauged catchments. *Hydrol. Sci. J.* **2019**, *64*, 1573–1587.

60. Gates, T.K.; Cox, J.T.; Morse, K.H. Uncertainty in mass-balance estimates of regional irrigation-induced return flows and pollutant loads to a river. *J. Hydrol. Reg. Stud.* **2018**, *19*, 193–210.
61. Vogt, R.J.; Sharma, S.; Leavitt, P.R. Direct and interactive effects of climate, meteorology, river hydrology, and lake characteristics on water quality in productive lakes of the Canadian Prairies. *Can. J. Fish. Aquat. Sci.* **2018**, *75*, 47–59.
62. Rico, A.; Arenas-Sánchez, A.; Alonso-Alonso, C.; López-Heras, I.; Nozal, L.; Rivas-Tabares, D.; Vighi, M. Identification of contaminants of concern in the upper Tagus river basin (central Spain). Part 1: Screening, quantitative analysis and comparison of sampling methods. *Sci. Total Environ.* **2019**, *666*, 1058–1070.
63. Ivanovsky, A.; Criquet, J.; Dumoulin, D.; Alary, C.; Prygiel, J.; Duponchel, L.; Billon, G. Water quality assessment of a small peri-urban river using low and high frequency monitoring. *Environ. Sci. Process. Impacts* **2016**, *18*, 624–637.
64. Jomaa, S.; Aboud, I.; Dupas, R.; Yang, X.; Rozemeijer, J.; Rode, M. Improving nitrate load estimates in an agricultural catchment using Event Response Reconstruction. *Environ. Monit. Assess.* **2018**, *190*, 330.
65. Jones, C. S.; Wang, B.; Schilling, K. E.; Chan, K.S. Nitrate transport and supply limitations quantified using high-frequency stream monitoring and turning point analysis. *J. Hydrol.* **2017**, *549*, 581–591.
66. van der Grift, B.; Broers, H.P.; Berendrecht, W.; Rozemeijer, J.; Osté, L.; Griffioen, J. High-frequency monitoring reveals nutrient sources and transport processes in an agriculture-dominated lowland water system. *Hydrol. Earth Syst. Sci.* **2016**, *20*, 1851–1868.
67. Drake, C.W.; Jones, C.S.; Schilling, K.E.; Amado, A.A.; Weber, L.J. Estimating nitrate-nitrogen retention in a large constructed wetland using high-frequency, continuous monitoring and hydrologic modelling. *Ecol. Eng.* **2018**, *117*, 69–83.

6. Discussion

Water is essential for humans and as well as for human activities such as drinking, agriculture and energy production. Quality of aquatic life is heavily dependent on the ambient water quality in our rivers, lakes and oceans. Unfortunately, human activities are causing different threats to our water bodies through improper land use practices, livestock activities, usage of herbicides and pesticides in agriculture etc. [1]. Eutrophication is relatively the most common and most, challenging environmental issue. It is caused by an excessive amount of phosphorus and nitrogen in water. Nutrients are essential for all living organisms, animals and plants to grow. Problem is initiated when too much nitrogen and phosphorus emits into the environment usually from human activities. The primary causes of nutrient pollution are fertilizer runoff from agricultural fields, animal waste e.g. return flow from livestock activities and agricultural lands [2]. High nutrient levels will result in higher growth of algae, as consequence algae will consume excessive amount of oxygen, that is necessary for fish and other aquatic organisms to survive. Excessive algae in water bodies will make water cloudy and reduces the photosynthetic radiation to deeper water levels, which in turn lead to oxygen depletion there.

Nutrient pollution also has effects on economy by affecting different sectors dependent on clean water, especially drinking water supply. Also in the Federal State of Mecklenburg-Vorpommern, diffuse nutrient pollution is a major concern. Despite enormous efforts, a large ratio of groundwater and surface water bodies still do not comply with the "good ecological status" according to the criteria of EU water framework directive. Concerning the chemical water quality, 76% of the monitored surface waters have at least a significant pollution with nitrate and 40% with phosphate [3], [4]. Nutrient levels in Tollense and its tributaries is a concern for achieving good chemical status of Tollense river. Phosphorous and nitrogen are two significant nutrients resulting from organic and inorganic fertilizers through livestock grazing, pesticides and disinfectants. Hydrological modelling in combination with mass balance assessment is important to understand the dynamics and transport and as well as to identify the critical pollution levels in the water body. To develop more effective measures to reduce nutrient emissions, input, transport and transformation processes must still be better understood, especially for a higher spatial and temporal resolution. This demands for an improved monitoring and modelling at regional and lower scale. Multiple studies have been made in north eastern lowlands of Germany with empirical and semi-distributed (e.g. SWAT and SWIM) models [5]–[13].

Current Hydrological and Mass Balance Study

Empirical tools and semi distributed and distributed hydrological models are used to study complex hydrological processes by the hydrologists. With the development of hydrology, trend has shifted from empirical hydrological models towards semi distributed and distributed hydrological models. Information and understanding provided by hydrological models is central to the successful management of surface and groundwater resources. Fully distributed models are capable of capturing the spatial distribution of input variables including meteorological conditions (rainfall, temperature etc) and physical parameters (land use, soil, elevation etc). So, distributed models are data intensive they need quality data, hard to configure and they require greater simulation and calibration time. The performance of these models is quite low in hydrological remote area (data scare regions). Semi-distributed models, they lump meteorological variables and physical parameters in to sub-basins, they are easy to setup and require shorter time relatively. Though it is hard to say one performed better than the other, after model parameter calibration both can provide a comparable result based on available data quality. The current study is a combination of empirical methods and physically based fully distributed coupled hydrological and hydrodynamic models. This study uses available low-frequency monitored flow and water quality data in combination with empirical and integrated hydrological and hydraulic modelling to represent the SW and GW hydrology and NO_3-N loads in Tollense River catchment.

Empirically Based Approach

In this study, initially an easier and more convenient method is used to make the comparison and integration of SW and GW quality data from monitoring networks. Though these approaches do not describe the processes itself but can combine available data with adapted conceptual approaches to get reliable estimates of the pathways. In this study, GW flow in a characteristic lowland river, the Augraben (a tributary of Tollense River), was estimated by using hydraulic gradient method and different hydrograph separation techniques. The hydraulic gradient method is based on aquifer characteristics and the measured hydraulic gradients in the river and nearby available boreholes. This method works well in local GW fluxes near to the gauging stations. However, it does not always represent reasonable estimations of GW flow in longer reaches. The hydrograph separation method takes into account the time series of river discharge and then divide it into base flow and quick flow [14]. Since separation methods are no process-based models, the interpretation of base flow and quick flow is often not distinct, especially concerning the interflow (e.g., drainage). This study is mainly focused to develop and apply a method to assess the contribution of GW to the nitrogen loads in SW based on available monitoring data. Based on analysis of data collected from monitoring programs indicates that GW is one of the dominant contributor to SW contamination in Augraben River catchment. The results of this preliminary evaluation are in line with the studies conducted in north eastern lowlands by Melanie MEWES [13] and Wendland et al. [12] have also found GW and drainage as a dominant source of diffuse pollution. Augraben river catchment analysis found a strong relationship between SW and GW quality. This means that GW improvement will result in improved standards of SW quality. Different other methods like flow difference method, tracer method etc., need to be considered in combination with gradient flow and flow hydrograph separation method as these are the simplest ways to quantify the GW role in total nitrogen loads in surface waters by just using the available monitoring data. For a better local resolution and process understanding, it would be beneficial to perform flow monitoring at the outlets of drainage channels small channels entering into the Augraben. It is also advisable to collect the GW concentration data in higher resolution than on a seasonal basis. This way, the correlation between land use and GW concentrations can be described more reliably by combining the data analysis and simple flow equations. Regarding the EU nitrate directive and EU WFD, the NO_3-N concentration in GW are twice over the limit at Au II Alt Kentzlin and requires maximum efforts to reduce NO_3-N pollution in the study area.

Physically Based Hydrological Modelling

Different hydrological models have been widely used all around the world to predict flow, sediment and nutrient load from watersheds of various sizes [15]–[23]. After getting preliminary results by applying the empirical models, in second stage of this study, bi-directional coupled hydrologic (MIKE SHE) and hydraulic (MIKE 11) model was applied to the Tollense River and Augraben River catchment, a tributary of the Tollense River. The Augraben River catchment represents common features of the European lowland catchments, such as shallow GW tables, GW and SW interactions, control structures, provision of artificial drainage, periodic inundation, etc. Due to these features, the modelling approach explained in the current study has a huge potential to simulate/predict the lowland response to anthropogenic activities and expected changing climatic conditions and to provide guidelines for better conservation and management practices of susceptible catchments.

In general, the coupled model performance in Tollense river catchment was satisfyingly able to describe the interacting hydrologic subsystems GW and SW, assessed by comparison with observed GW levels and SW discharges. Modelling results demonstrate a close association between P, ET, SW discharges and GW levels. Despite the good representation of SW and GW dynamics, coupled model performance was not equally same in all the sub catchments due to heterogeneity of soils and variable availability of field monitoring data. Grid resolution is very important to define the heterogeneity of the catchment according to the desired level of complexity. The finally selected resolution was based on a good compromise between simulation time, numeric robustness and resulted accuracy. But even with a very fine grid it would not feasible to represent small scale variations of geology, which is only exactly known at the borehole locations from the drilling documents. Beside the required interpolation/generalization of geology, necessary estimates on the exact layout of the artificial drainage and drainage time constants are further uncertainty factors of the GW model. Due to private rights of the farmer's drainage maps were not available during the study, artificial drainage was constructed based on lowest points of DEM in the defined lowland catchment. Calibration process showed that river flows are very responsive to the Manning's n, drainage time constant and leakage coefficients. Water balance estimation during dry and wet years showed the interaction of different water balance components, where ET is a major water loss component and during dry years it reaches up to 65% of total water budget and results in lowering of GW levels due to contribution of GW to SW discharges under minimum GW recharge rates. Coupled model satisfactorily represented the water balance with an error of less than 2% of total water budget.

GW and SW interactions based on coupled model resulted intense interactions among SW and GW. Long term, SW flows follow the pattern of GW levels in the defined catchment with the higher GW flows followed by higher SW discharges. Model calibration of SW discharges was difficult due to the limited monitoring data availability of SW discharges and that highlights the significance of high resolution field monitoring data in hydrological modelling. GW is a major contributor to balance the SW flows during the low flow periods and GW contribution rises up to 45% of total SW flows during observed partial drought in the catchment and with exclusion of river flows from lake Tollense, GW contributes mainly to the Tollense river nearly up to 95% of total SW flows.

The simulated hydrograph shows relatively overestimated river flows during peak flow periods. A successful calibration of SZ boundary conditions and geological layers' vertical discretization, saturated hydraulic conductivities, drainage time constant and leakage coefficient play a vital role to successfully quantify the SW and GW interactions. The above discussed differences between simulated and monitored GW levels and SW discharges are due to a combination of different sources of uncertainty: Structural (grid size, simplification of geology), Input data (climate data) and Parameter uncertainty: (e.g. saturated hydraulic conductivity).

The NO_3-N pollution of SW and GW is a major environmental problem, especially in lowlands with intensive agriculture and related farm activities. Achievement of environmental sustainability requires the detailed assessment of spatial and temporal variation of water quality at the catchment and regional scale. River mass balance methods using observed or simulated flows and pollutant concentrations can be helpful in describing the magnitude and extent of existing pollutant loads along a river [24], [25]. Based on coupled hydrological and hydraulic model results, we have successfully estimated the NO_3-N loads at the catchment and sub-catchment scale by combining low frequency monitoring data with hydrological modelling. GW levels were available at only two monitoring stations. In terms of water quality assessment and its variations at a catchment scale, limited monitoring data were available. This enhances both the explanatory strength of generally available and inexpensive quantitative hydrological data and the (so far, only) qualitative status information from grab sampling [26]. The responses of NO_3-N and P concentrations can be plausibly linked to the hydrological dynamics of SW and GW, triggered by the meteorological input. Combining these data with measured emission data of WWTP, a trustworthy source apportionment between diffuse and known point sources is feasible. In summertime, the measured load is lower than the predicted sum. The difference can be a rough estimate of NO_3-N transformations and plant uptake rates. The results of this study demonstrate, in line with similar studies with low frequency monitoring data [27-28], that using the explanatory strength of quantitative hydrological data can significantly improve load estimates.

Key Problems in Integrated Hydrological and Hydrodynamic Modelling

Key problems associated with coupled hydrological and hydraulic modelling The advantages of a physical distributed model go along with requiring extensive hydrological input data, high computing capabilities and long computational times and thus increases the overall effort to successfully setup and calibrate the model. Input grid discretization is a priori in MIKE SHE and has to be selected wisely regarding available data, required accuracy and computational effort. Like other hydrological models such as SWAT, MIKE SHE can also simulate catchments size up to thousands of km^2 , but for physical distributed models this increases the spatially distributed input data even more than models based on hydrological response units (HRU) do. Like semi distributed models, MIKE SHE cannot represent sub-grid heterogeneity. In case of limited data availability, satellite data can be very helpful for topography and land use estimation but additional terrestrial data acquisition e.g. soil, climatic, aquifer data etc., needs to be gathered. Lack of detailed river cross sections, variation of seasonal Manning's n, drainage maps and leakage coefficient rates impacts the simulated river flows. Limited availability of GW boreholes and monitored GW levels to produce GW contour maps makes it harder to delineate the GW divide and it is sometimes possible to have cross boundary GW flows. Calibration and validation efforts increase enormously in physically distributed models with limited observed data, risking to compensate structural model errors with incorrect model parameterization. Sufficient amount of observed monitoring data will help to provide ease in model setup and during calibration process.

Coupled Model Performance and Transferability

Coupled model MIKE SHE and MIKE 11 model has demonstrated its potential to simulate hydrological processes common within lowlands. The results of the current study in terms of need for further studies to achieve EU-WFD, dominant pollution pathways, and identification of critical areas requiring extra attention are in line with previous studies conducted in north eastern lowland catchments. The coupled model has successfully identified the critical areas requiring maximum attention in accordance with the recent study conducted by German authorities in MV [29]. Extensive data requirements are potential problems to apply coupled physically distributed models in other lowland catchments. Some of the data used in this study is freely available in Germany such as some of the geo-data and climate data provided by DWD (German weather service) platform and can be used for other lowlands in Germany. Manning's n values can be obtained from literature and can be used in other similar catchments. Soil properties were obtained from local environmental protection agency; literature values or field investigations are required for sites with different soil properties. In Europe high resolution DEM model can be obtained from local environmental offices. Lack of detailed river cross sections can be compensated with cross sections based on DEM. Hydraulic structure dimensions can be roughly estimated with Google earth in case of missing information. Calibration of SW discharges and GW flows require monitoring data and there is no other authentic alternative rather than field investigations in the study area.

Key Contributions

The key contribution of this study includes Development and calibration of a physically based distributed coupled model to describe the lowlands hydrology as integrated hydrological and hydraulic modelling has rarely been done in the north eastern region of Germany. The ability of physically based coupled models to describe the lowland hydrology is demonstrated. Simultaneous calibration of SW and GW with a physically based integrated hydrological model proves the robustness and reliability of an integrated model. SW and GW interaction during dry and wet hydrological years in lowlands can be reliably modelled, which is important with regard to the expected and already ongoing change of climatic conditions. SW discharges and GW flows can be extrapolated at ungauged sites on a physical basis. The method of coupled modelling, including the steps of model setup and calibration can be transferred to other sites with comparable characteristics. Land use management practices and their results on SW and GW dynamics can be quantified.

References

[1] C.W. Fetter, K.L (1994). Applied hydrology. Englewood cliffs, Prentice Hall. Novotny, V., 1999. Diffuse pollution from agriculture-a worldwide outlook. Water Sci. Technol. 39(3), 1–13.

[2] Q. D. Lam, B. Schmalz, and N. Fohrer, "The impact of agricultural Best Management Practices on water quality in a North German lowland catchment," *Environ. Monit. Assess.*, vol. 183, no. 1–4, pp. 351–379, 2011, doi: 10.1007/s10661-011-1926-9.

[3] Brook Zarnow gauging station Zarnow basin, Germany. Retrieved from http://nefriend.bafg.de/servlet/is/17796/Zarnow.pdf.

[4] Koch F (2014) Diffuse Nährstoffbelastungen in Oberflächengewässern und im Grundwasser, 19. Gewässersymposium, 19.11.2014 Güstrow.

[5] C. Hesse and V. Krysanova, "Modeling climate and management change impacts on water quality and in-stream processes in the Elbe river basin," *Water (Switzerland)*, vol. 8, no. 2, pp. 1–31, 2016, doi: 10.3390/w8020040.

[6] Krause, S., & Bronstert, A. (2007). The impact of groundwater–surface water

interactions on the water balance of a mesoscale lowland river catchment in northeastern Germany. Hydrological Processes: An International Journal, 21(2), 169-184.

[7] V. Krysanova and A. Becker, "Integrated modelling of hydrological processes and nutrient dynamics at the river basin scale," *Hydrobiologia*, vol. 410, pp. 131–138, 1999, doi: 10.1023/A:1003728419934.

[8] S. Koch, A. Bauwe, and B. Lennartz, "Application of the SWAT Model for a Tile-Drained Lowland Catchment in North-Eastern Germany on Subbasin Scale," *Water Resour. Manag.*, vol. 27, no. 3, pp. 791–805, 2013, doi: 10.1007/s11269-012-0215-x.

[9] J. Kiesel, N. Fohrer, B. Schmalz, and M. J. White, "Incorporating landscape depressions and tile drainages of a northern German lowland catchment into a semi-distributed model," *Hydrol. Process.*, vol. 24, no. 11, pp. 1472–1486, 2010, doi: 10.1002/hyp.7607.

[10] B. Schmalz, F. Tavares, and N. Fohrer, "Modelling hydrological processess in mesoscale lowland river basins with SWAT - Capabilities and challenges," *Hydrol. Sci. J.*, vol. 53, no. 5, pp. 989–1000, 2008, doi: 10.1623/hysj.53.5.989.

[11] B. Guse, M. Pfannerstill, and N. Fohrer, "Dynamic Modelling of Land Use Change Impacts on Nitrate Loads in Rivers," *Environ. Process.*, vol. 2, no. 4, pp. 575–592, 2015, doi: 10.1007/s40710-015-0099-x.

[12] Wendland F., Keller L., Kuhr P., Kunkel R., Tetzlaff B. (2015) Regional differenzierte Quantifizierung der Nährstoffeinträge in das Grundwasser und in die Oberflächengewässer Mecklenburg-Vorpommerns unter Anwendung der Modellkombination GROWADENUZ-WEKU-ME.

[13] Rostock. Meeresbiolog. Beitr (2004). Nährstoffausträge in die Ostsee aus diffusen Quellen Mecklenburg-Vorpommerns und Schleswig-Holsteins Nutrient emissions from diffuse sources of Mecklenburg-West Pomerania and Schleswig-Holstein to the Baltic Sea.

[14] Methods for estimating GW discharge to streams – summary of field trials.

[15] Arnold, J. G., Srinivasan, R., Muttiah, R. S., & Williams, J. R. (1998). Large area hydrologic modelling and assessment. Part I. Model development. Journal of the American Water Resources Association, 34(1), 73–89.

[16] Saleh, A., Arnold, J. G., Gassman, P. W., Hauck, L. W., Rosenthal, W. D., Williams, J. R., et al. (2000). Application of SWAT for the upper North Bosque River watershed. Transactions of the ASAE, 43(5), 1077–1087.

[17] Tripathi, M. P., Panda, R. K., Raghuwanshi, N. S., & Singh, R. (2004). Hydrological modeling of a small watershed using generated rainfall in the soil and water assessment tool model. Hydrological Processes, 18, 1811– 1821.

[18] Gassman, P. W., Osei, E., Saleh, A., Rodecap, J., Norvell, S., & Williams, J. (2006). Alternative practices for sediment and nutrient loss control on livestock farms in northeast Iowa. Agriculture, Ecosystems & Environment, 117(2–3), 135–144.

[19] Lenhart, T., Fohrer, N., & Frede, H.-G. (2003). Effects of land use changes on the nutrient balance in mesoscale catchments. Physics and Chemistry of the Earth, 28, 1301–1309.

[20] Schmalz, B., Tavares, F., & Fohrer, N. (2008b). Modelling hydrological lowland processes in mesoscale river basins with SWAT—Capabilities and challenges. Hydrological Sciences Journal, 53(5), 989–1000.

[21] SCS (Soil Conservation Service) (1972). Section 4: Hydrology in national engineering handbook (pp. 1–30).

[22] GRASS 4.1. Reference Manual. US Army Corps of Engineers. Construction Engineering Research Laboratories, Champaign, Illinois, 1993.

[23] Krysanova V, Hattermann F, Wechsung F. Development of the ecohydrological model SWIM for regional impact studies and vulnerability assessment. Hydrological Processes: An International Journal, 2005, 19(3): 763-783.

[24] Vogt, R.J.; Sharma, S.; Leavitt, P.R. Direct and interactive effects of climate, meteorology, river hydrology, and lake characteristics on water quality in productive lakes of the Canadian Prairies. Can. J. Fish. Aquat. Sci. 2018, 75, 47–59.

[25] Gates, T.K.; Cox, J.T.; Morse, K.H. Uncertainty in mass-balance estimates of regional irrigation-induced return flows and pollutant loads to a river. J. Hydrol. Reg. Stud. 2018, 19, 193–210.

[26] Rico, A.; Arenas-Sánchez, A.; Alonso-Alonso, C.; López-Heras, I.; Nozal, L.; RivasTabares, D.; Vighi, M. Identification of contaminants of concern in the upper Tagus river basin (central Spain). Part 1: Screening, quantitative analysis and comparison of s.

[27] Jomaa, S.; Aboud, I.; Dupas, R.; Yang, X.; Rozemeijer, J.; Rode, M. Improving nitrate load estimates in an agricultural catchment using Event Response Reconstruction. Environ. Monit. Assess. 2018, 190, 330.

[28] Ivanovsky, A.; Criquet, J.; Dumoulin, D.; Alary, C.; Prygiel, J.; Duponchel, L.; Billon,

G. Water quality assessment of a small peri-urban river using low and high frequency monitoring. Environ. Sci. Process. Impacts 2016, 18, 624–637.

[29] Stickstoff im Wasser: Hier dürfen viele Bauern in MV bald weniger düngen. Retrieved from https://www.ostsee-zeitung.de/Nachrichten/MV-aktuell/Stickstoff-im-Wasser-Viele-Bauern-in-MV-duerfen-bald-weniger-duengen (accessed on 6 December 2020).

7. Conclusions and Proposed Directions of Future Research

Conclusions

To achieve a sustainable watershed management in accordance with EU WFD goals this research is conducted in north eastern Germany lowland catchment. The current study quantified detailed water and mass balance both with empirically based and physically distributed models. Base on hydrological and hydraulic modelling the following general conclusions have been drawn

- Empirically based robust hydrograph separation models can provide reasonable results with the pre-condition of high spatio-temporal monitoring data availability. In areas of limited spatio-temporal data availability, empirically based models cannot provide reliable results as these models are not based on hydrological considerations instead process the flow hydrograph as a signal. These models can provide effective estimation of the long term behavior (e.g., on annual basis) of base flow and SW runoff to total runoff. However, conceptual and empirical base flow separation methods cannot be a replacement against physically based hydrological models.
- Process-based hydrological modelling can define in detail SW and GW interactions, and can reliably simulate the SW discharges and GW levels at ungauged locations. These models are data demanding and requires high calibration efforts but can be transferred to other catchments and can be calibrated according to local conditions. The modelling framework presented in this study based on hydrological modelling and water quality monitoring can be used to develop future strategies to improve the water quality management by assessing the dominant nutrient entry pathways contributing to the SW pollution.

Study Area Specific Conclusions

- Enormous interaction between GW, SW, P and ET exists. The detailed water balance results show that GW is a main contributor to the SW discharges especially during periods with low SW flows.
- Contribution of GW and point sources to SW pollution by combing monitored data and hydrological modelling found that the ability to perform source separation techniques (quantification of SW and GW flows and respective loads) in winter are quite good, while in summer strong influence of instream transformation is

estimated. However, this can only be seen, when the emissions and the resulting rive loads are estimated separately.

Proposed Directions of Future Research

The possible research directions in the future may relate to a more complex research matrix of improved hydrological and water quality modelling; high spatio-temporal sample collection; future forecast of discharge and GW levels under climate and land-use change; best agriculture management practices; and economic impact assessment of eutrophication.

- ***Hydrological modelling:*** The hydrological modelling to simulate the detailed water balance needs to concentrate on the use of a finer grid size to get a better insight in the SW and GW dynamics and interactions. Applying a high-resolution DEM would provide a more accurate results e.g. to make flood maps and to simulate real flood conditions in a catchment.
- ***Water quality modelling:*** Land-use management practices and their results on SW and GW dynamics quantified in this study. Further addition of a nutrient transport model is intended and will help to study the SW and GW quality under different land-use scenarios. The hydrological and water quality models review made in this study can be used for further studies involving water quality modelling tools.
- ***High spatio-temporal sample collection:*** Short-term dynamics of SW quality variations are not captured by common low-frequency grab sampling. The low-frequency monitoring provides an overview of the average concentrations of chemical species and suggests some general processes that may explain the observed data. The added value of high-frequency monitoring is the possibility of capturing diurnal cycles and transient events that help relate the causes and effects of human activities and storms. High-frequency monitoring can go much further in the interpretation of the data and can more precisely uncover and/or confirm rapid processes at work in the system.
- ***Future forecast of discharge and GW levels under climate and land-use change:*** Process-based hydrological models in combination with statistical models needs to be applied on calibrated SW discharges and GW levels under the influence of different land-use and climate change scenarios to predict the long terms behavior of SW and GW hydrology in the study area.

- ***Best agriculture management practices:*** Further studies need to focus that the environmental research modelling and environmental practice should go hand in hand for the sake of both agriculture and environment.

Economic value assessment of eutrophication: Further studies should include the economic impact assessment of higher SW NO_3-N levels and resulted eutrophication in terms of loss of tourism, fishing, and expenditures on water quality improvement program.

Appendix A.

Review summary of the selected modelling tools based on their ability to simulate the lowland catchments.

Hydrological Processes			
SWAT	**SWIM**	**HSPF**	**MIKE SHE**
Interception	-	Interception	Interception
Evapotranspiration (ET)	Evapotranspiration	Evapotranspiration	Evapotranspiration
Infiltration (I)	Infiltration	Infiltration	Infiltration
Percolation	Percolation	Percolation	Percolation
Subsurface flow	Subsurface flow	Subsurface flow	Subsurface flow
Baseflow	Baseflow	Baseflow	Baseflow
Surface runoff	Surface runoff	Surface runoff	Surface runoff
Drainage	-	-	Drainage
Pump flow	-	-	Pump flow
Urban drainage	-	-	Urban drainage
Hydraulic processes			
SWAT	**SWIM**	**HSPF**	**MIKE SHE and MIKE 11**
-	-	-	River Pumps
-	-	-	Backwater effect
-	-	-	Control structures
-	-	-	Operational strategies

Governing Equations	
SWAT	
Runoff volume	Modified Soil Conservation Service (SCS) Curve Number or Green and Ampt infiltration equation
Peak runoff rate	Rational formula or the SCS TR-55 method
Subsurface flow and percolation	Kinematic storage routine equation; is based on several input data regarding hillslope, field capacity, the volume of soil water, soil porosity, and hydraulic conductivity

Potential evapotranspiration	• Hargreaves equation • Priestley–Taylor equation • Penman–Monteith equation
Flow rate and velocity	• Manning's equation
Sediment yield	Modified Universal Soil Loss Equation
Flow routing	"Muskingum routing method" or "variable storage routing method"
SWIM	
Surface runoff	The non-linear function of precipitation and a retention coefficient
Subsurface flow	Kinematic storage routine equation
Potential evapotranspiration	Priestley–Taylor or Penman–Monteith
Sediment yield	Modified Universal Soil Loss Equation
HSPF	
Infiltration	Empirical method based on the type of soil and available storage
Flow rate and velocity	Manning's equation
Flow routing	Kinematic wave routing or storage routing
MIKESHE	
Surface runoff	1D diffusive wave Saint Venant equation
Unsaturated zone flow	• Richards equation • Gravity flow • Two-layer water balance method
Saturated zone flow	• 3D finite difference method • Linear reservoir method
Overland flow	2D finite difference diffusive wave equation
Evapotranspiration	Kristensen and Jensen method Two-Layer UZ/ET module
Flow routing	• No routing • Muskingum method • Muskingum–Cunge method
Difficulties or Limitations	

SWAT	• SWAT does not simulate sub-daily events; e.g., a single storm event or flood routing of a single event. • SWAT does not model the denitrification process during water quality modelling. • SWAT does simulate organic P and inorganic P, but takes into account the adsorption or desorption of inorganic P to particles.			
SWIM	• SWIM does not simulate the water quality of reservoirs, ponds, and lakes • Simulation accuracy is not only directly related to the grid size of the spatial input data, but it is also determined by optimal model parameters			
HSPF	• SWIM simulates many physical processes based on empirical relations. • Metrological factors affect the model results' accuracy • Limited to 1D flows and well-mixed rivers • Insensitive to spatial variations			
MIKE SHE	• Extensive input data requirements			
Input data				
SWAT				
Climate	**Hydrogeology**	**Soil data**	**Land use**	**Topography**
Daily precipitation	Groundwater table height	Soil thickness or depth	Land use/land cover	Digital elevation model (DEM)
Air temperature (max and min)	Aquifer storage	Bulk density	Leaf area index (LAI)	-
Solar radiation	Drainage	Soil moisture content	Plant root depth (RD)	-
Wind speed	Irrigation	Soil hydraulic conductivity	-	

Evapotranspiration	Saturated hydraulic conductivity	Porosity	-	-
Humidity	Groundwater recharge	Soil texture	-	-
-	Aquifer specific yield	-	-	-
-	Groundwater abstraction rates	-	-	-
SWIM				
Climate	**Hydrogeology**	**Soil data**	**Land use**	**Topography**
Precipitation	Groundwater table height	Soil thickness or depth	Land use/land cover	Digital elevation model (DEM)
Air temperature (max, min, and average)	Aquifer storage	Bulk density	Leaf area index (LAI)	-
Solar radiation	Drainage	Soil moisture content	Plant root depth (RD)	-
Evapotranspiration	Saturated hydraulic conductivity	Soil hydraulic conductivity	-	-
-	Groundwater recharge	Porosity	-	-
-	Aquifer specific yield	Field capacity	-	-
-	-	Wilting point	-	-
HSPF				
Climate	**Hydrogeology**	**Soil data**	**Land use**	**Topography**

Precipitation	surface water storage	Soil thickness or depth	Land use/land cover	Digital elevation model (DEM) or sub-basin area and average slope
Air temperature	Aquifer storage	Bulk density	-	
Dew point temperature	PH	Soil moisture content	-	
Solar radiation	Subsurface flow storage	Soil hydraulic conductivity	-	
Wind speed	-	Infiltration capacity	-	-
Evapotranspiration	-	Soil texture	-	-
Humidity	-	-	-	-
Vapor pressure	-	-	-	-
MIKE SHE				
Climate	**Hydrogeology**	**Soil data**	**Land use**	**Topography**
Precipitation	Groundwater table	Geological layers	Land use/land cover	Digital elevation model (DEM)
Air temperature	Aquifer storage	Bulk density	Vegetation type	-
Solar radiation	Specific yield	Soil moisture content	Vegetation height	-
Wind speed	Saturated hydraulic conductivity	Soil hydraulic conductivity	Leaf area index	-
Evapotranspiration	Groundwater extraction	Porosity	Root depth	-
Humidity	Groundwater recharge rate	Soil texture	-	-
Vapor pressure	Drainage	-	-	-

Daily sunshine hours	Irrigation	-	-	-
-	Depth of the saturated zone	-	-	-
-	Capillary storage	-	-	-
Spatial and temporal discretization				
SWAT	**SWIM**	**HSPF**	**MIKE SHE**	
Spatial: Flexible, Temporal: Continuous	Spatial: Flexible, Temporal: Daily	Spatial: Flexible, Temporal: Flexible or user-defined time step	Spatial: Flexible, Temporal: Event-based and continuous	
Basic Purpose				
SWAT	SWAT's principle purpose is to compute runoff and loadings from rural areas and watersheds with intensive agriculture. SWAT evaluates the effects of different management practices and decisions on water resources, as well as agricultural pollutants in large river catchments.			
SWIM	The SWIM model was established to examine the impacts of climate and land-use changes at the regional level.			
HSPF	The HSPF model was developed to simulate both catchment hydrology and water quality.			
MIKE SHE	The key purpose of the MIKE SHE model is the integrated modelling of evapotranspiration, groundwater, surface water, and groundwater recharge.			

Curriculum Vitae

Muhammad Waseem

Personal Information

Address: Erich Schlesinger Street 20, Room # 10-1-2, 18059, Rostock, Germany

Mobile: +4917924442232

E-mail: waseem.rostock@gmail.com

Date of Birth: 30-March-1989

Nationality: Pakistani

Driving License: Yes

Profile

- Highly self-motivated academic researcher with demonstrated research expertise in surface and subsurface hydrology
- Advanced competence in filed work and in integrated hydrological modelling
- Experience in process designing and experimental setup with a knack of using programming tools
- Skilled in project management, detailed report writing and different phases of research projects

Education

2016-2020*	*Doctor of Engineering (Dr.-Ing.)* Department of Water Management University of Rostock, Germany **Thesis Title:** Integrated Hydrological and Mass Balance Assessment in a German Lowland Catchment with a Coupled Hydrologic and Hydraulic Modelling **Field of Study:** Hydrology and Water Resources Management, Hydrological Modelling
2013-2015	*Master of Science (MSc) in Water Resources and Environmental Management* Leibniz University Hannover, Germany **Thesis Title:** Ground Water Contamination due to Unhealthy Sanitary **Grade:** 2.18 (Max: 1 & Min: 4) Standing: Good **Field of Study:** Water and Environmental Management, Hydrology
2010-2013	*Master of Science (MSc) in Water Resources Engineering* University of Engineering & Technology Lahore, Pakistan **Thesis Title:** Study of Benching Phenomenon at Upstream Slope of Mangla Dam **Percentage:** 67% **Field of Study:** Irrigation Engineering & Management, Applied Hydrology, Dam & Reservoir Engineering
2006-2010	*Bachelor of Science (BSc) in Agricultural Engineering* Bahauddin Zakaryia University, Multan, Pakistan **Project Title:** High efficiency irrigation systems and their installation **Grade:** 3.47 - with distinction (Max: 4 & Min: 1) **Field of Study:** Environmental Engineering, Surface and Groundwater Hydrology, Industrial Pollution & Its Control, Water Management
2004-2006	*Intermediate in Pre-Engineering Group (University Entrance Qualification)* Board of Intermediate and Secondary Education, Multan, Pakistan **Percentage:** 61% **Major Subjects:** Mathematics, Chemistry, Physics

Research and Professional Experience

03/2016-09/2019	***Scientific Research Assistant*** University of Rostock, Germany **Project title:** Boat Monitoring _ Recording and reducing the material pollution of rivers in rural areas • Data collection from authorities and from local farmers • Hydrological modelling • Groundwater and surface water sampling and analysis • GIS based maps • River cross sections with ADCP • Soil Sampling and analysis
06/2010-04-2011	***Design Engineer*** Drip Irrigation System Corporation Islamabad, Pakistan • Design of drip and sprinkler irrigation system • Installation of drip and sprinkler irrigation system
02/2010-04/2010	***Internee*** ALI AKBAR GROUP, Lahore, Pakistan • Marketing and design of high efficiency irrigation system
06/2009-08/2009	***Internee*** On Farm Water Management, Vehari, Pakistan • Survey and Design of Water Courses • Cost Estimation • Laser Land Levelling

Scientific Publications (In Peer-Reviewed Journals)

Waseem, M., Schilling, J., Kachholz, F., & Tränckner, J. (2020). Improved Representation of Flow and Water Quality in a North-Eastern German Lowland Catchment by Combining Low-Frequency Monitored Data with Hydrological Modelling. *Sustainability*, *12*(12), 4812. https://doi.org/10.3390/su12124812 (Impact Factor =2.592)

Waseem, M., Kachholz, F., Klehr, W., & Tränckner, J. (2020). Suitability of a Coupled Hydrologic and Hydraulic Model to Simulate Surface Water and Groundwater Hydrology in a Typical North-Eastern Germany Lowland Catchment. *Applied Sciences*, *10*(4), 1281. https://doi.org/10.3390/app10041281 (Impact Factor =2.217)

Waseem, M., Kachholz, F., & Traenckner, J. (2018). Suitability of common models to estimate hydrology and diffuse water pollution in North-eastern German lowland catchments with intensive agricultural land use. *Frontiers of Agricultural Science and Engineering*, *5*(4), 420-431. https://doi.org/10.15302/J-FASE-2018243 (Impact Factor =0.60)

Waseem, M., Koegst, T., & Tränckner, J. (2018). Groundwater Contribution to Surface Water Contamination in a North German Low Land Catchment with Intensive Agricultural Land Use. *Journal of Water Resource and Protection*, *10*(03), 231. https://doi.org/10.4236/jwarp.2018.103014 (Impact Factor =1.27)

Waqas, M. M., Shah, S. H. H., Awan, U. K., **Waseem, M.**, Ahmad, I., Fahad, M., ... & Ali, S. (2020). Evaluating the Impact of Climate Change on Water Productivity of Maize in the Semi-Arid Environment of Punjab, Pakistan. *Sustainability*, *12*(9), 3905. https://doi.org/10.3390/su12093905 (Impact Factor =2.592)

Andiego, G., **Waseem, M.**, Usman, M., & Mani, N. (2017). The Influence of Rain Gauge Network Density on the Performance of a Hydrological Model. *Computational Water, Energy, and Environmental Engineering*, *7*(1), 27-50. https://doi.org/10.4236/cweee.2018.71002 (Impact Factor =1.42)

Waseem, M., Mani, N., Andiego, G., & Usman, M. (2017). A review of criteria of fit for hydrological models. *International Research Journal of Engineering and Technology (IRJET)*, *4*(11), 1765-1772.

Scientific Publications (Under Review in Peer-Reviewed Journals)

Manuscript Title: Appraisal of Climate Change Impact on Water Resources of Pakistan: A Case Study of Mangla Watershed (under review in impact factor journal: Atmosphere).

Projects Currently Working

- Groundwater Mapping

Planned Paper: Groundwater mapping in Pakistan

- Rainwater Harvesting and its role in reducing urban floods

Planned Paper: Roof rainwater harvesting potential in urban areas of Pakistan

- Water Quality Modelling

Planned Paper: Impact of pit latrines on the fecal contamination of drinking ground water wells in rural areas of southern Punjab, Pakistan

Soft Skills

- MIKESHE (Integrated surface and subsurface hydrological modelling)
- MIKE 11 (River modelling)
- MOD FLOW (Assessment of ground water contamination from a contamination source)
- R STUDIO (Statistical tests)
- Office Tools: MS Word, MS PowerPoint, MS Excel, LaTex

References

- Prof. Dr.-Ing. habil. Jens Tränckner

Universität Rostock

jens.traenckner@uni-rostock.de

https://www.auf.uni-rostock.de/professuren/h-w/wasserwirtschaft/leitung/

- Prof. Dr. rer. nat. Konrad Miegel

Universität Rostock

konrad.miegel@uni-rostock.de

https://www.auf.uni-rostock.de/professuren/h-w/hydrologie-und-angewandte-meteorologie/mitarbeiter/

- Prof. Dr. Christine Staple

Universität Rostock

christine.stapel@uni-rostock.de

In dieser Reihe bisher erschienen

Band I
10. DIALOG Abfallwirtschaft MV
– Von der Abfallwirtschaft zur Energiewirtschaft.
Tagungsband, erschienen im Juni 2007, ISBN 987-3-86009-004-6

Band II
Ellen-Rose Trübger
Entwicklung eines Ansatzes zur Berücksichtigung der ungesättigten Zone bei der Grundwassersimulation von Feuchtgebieten.
Dissertation, erschienen im August 2007, ISBN 978-3-86009-006-0

Band III
René Dechow
Untersuchungen verschiedener Ansätze der Wasserhaushalts- und Stofftransportmodellierung hinsichtlich ihrer Anwendbarkeit in Stickstoffhaushaltsmodellen.
Dissertation, erschienen im September 2007, ISBN 978-3-86009-016-9

Band IV
Carolin Wloczyk
Entwicklung und Validierung einer Methodik zur Ermittlung der realen Evapotranspiration anhand von Fernerkundungsdaten in Mecklenburg-Vorpommern.
Dissertation, erschienen im September 2007, ISBN 978-3-86009-009-1

Band 5
1. Rostocker Bioenergieforum.
Bioenergieland Mecklenburg-Vorpommern.
Tagungsband, erschienen im Oktober 2007, ISBN 978-3-86009-013-8

Band 6
Kulturtechniktagung 2007.
Ostseeverschmutzung und Flächenentwässerung.
Tagungsband, erschienen im Januar 2008, ISBN 978-3-86009-018-3

Band 7
Enrico Frahm
Bestimmung der realen Evapotranspiration für Weide (Salix spp.) und Schilf (Phragmites australis) in einem nordostdeutschen Flusstalmoor.
Dissertation, erschienen im Mai 2008, ISBN 978-3-86009-023-7

Band 8
Jenny Haide
Methode zur Quantifizierung der Einflüsse auf Vorgangsdauern lohnintensiver Arbeiten am Beispiel von Pflasterarbeiten.
Dissertation, erschienen im Juni 2008, ISBN 978-3-86009-024-4

Band 9
11. DIALOG Abfallwirtschaft MV
Chancen und Risiken für die deutsche Abfallwirtschaft im Ausland.
Tagungsband, erschienen im Juni 2008, ISBN 978-3-86009-029-9

Band 10
Stefan Cantré
Ein Beitrag zur Bemessung geotextiler Schläuche für die Entwässerung von Baggergut.
Dissertation, erschienen im Juni 2008, ISBN 978-3-86009-032-9

Band 11
Birgit Wüstenberg
Praxis der Standortwahl von Sportboothäfen im Küstenbereich Mecklenburg-Vorpommerns und Entwicklung einer Bewertungsmethode als Planungshilfe.
Dissertation, erschienen im Juli 2008, ISBN 978-3-86009-033-6

Band 12
André Clauß
Erhöhung der Trinkwasserversorgungssicherheit in Havarie- und Krisensituationen durch neue Handlungsalgorithmen sowie Einbeziehung bisher ungenutzter Ressourcen am Beispiel von Bergbaugrubenwasser.
Dissertation, erschienen im September 2008, ISBN 978-3-86009-037-4

Band 13
Peter Degener
Sickerwasserkreislauf zur Behandlung von Sickerwässern der aerob-biologischen Restabfallbehandlung (Restabfallrotte).
Dissertation, erschienen im Oktober 2008, ISBN 978-3-86009-043-5

Band 14
2. Rostocker Bioenergieforum
Innovationen für Klimaschutz und wirtschaftliche Entwicklung.
Tagungsband, erschienen im Oktober 2008, ISBN 978-3-86009-044-2

Band 15
7. Rostocker Abwassertagung
Fortschritte auf dem Gebiet der Abwasserentsorgung.
Tagungsband, erschienen im November 2008, ISBN 978-3-86009-045-9

Band 16
Christian Noß
Strömungsstrukturen kleiner naturnaher Fließgewässer unter Berücksichtigung von Turbulenztheorie und Dispersionsmodellen.
Dissertation, erschienen im Januar 2009, ISBN 978-3-86009-054-1

Band 17
Ralf Schröder
Entwicklung von Möglichkeiten zur Messung der N2-Übersättigung sowie Methoden zur Reduzierung der Schwimmschlammbildung.
Dissertation, erschienen im Februar 2009, ISBN 978-3-86009-055-8

Band 18
Elmar Wisotzki
Bodenverfestigungen mit Kalk-Hüttensand-Gemischen.
Dissertation, erschienen im April 2009, ISBN 978-3-86009-059-6

Band 19
Ramez Mashkouk
Untersuchungen zur Adsorption und biologischen Aktivität an Aktivkohlefilter unter den Bedingungen der Wasseraufbereitung im Wasserwerk Rostock.
Dissertation, erschienen im April 2009, ISBN 978-3-86009-060-2

Band 20
Torsten Birkholz
Handlungserfordernisse und Optimierungsansätze für kommunale Ver- und Entsorgungsunternehmen im Zusammenhang mit demografischen Veränderungen im ländlichen Raum aufgezeigt an einem Beispiel in Mecklenburg-Vorpommern.
Dissertation, erschienen im Mai 2009, ISBN 978-3-86009-061-9

Band 21
12. DIALOG Abfallwirtschaft MV
Aktuelle Entwicklungen in der Abfallwirtschaft.
Tagungsband, erschienen im Juni 2009, ISBN 978-3-86009-062-6

Band 22
Thomas Fritz
Entwicklung, Implementierung und Validierung eines praxisnahen Verfahrens zur Bestimmung von Biogas- bzw. Methanerträgen.
Dissertation, erschienen im Oktober 2009, ISBN 978-3-86009-065-7

Band 23
3. Rostocker Bioenergieforum
Bioenergie – Chance und Herausforderung für die regionale und globale Wirtschaft.
Tagungsband, erschienen im Oktober 2009, ISBN 978-3-86009-065-8

Band 24
Muhammad Mariam
Analyse von Gefahrenpotenzialen für die Trinkwasserversorgung der Stadt Rostock unter besonderer Berücksichtigung von Schadstoffausbreitungsvorgängen in der Warnow.
Dissertation, erschienen im Februar 2010, ISBN 978-3-86009-078-7

Band 25
Manja Steinke
Untersuchungen zur Behandlung von Abwässern der Fischverarbeitungsindustrie.
Dissertation, erschienen im Juni 2010, ISBN 978-3-86009-085-5

Band 26
13. DIALOG Abfallwirtschaft MV
Die Kreislauf- und Abfallwirtschaft im Wandel. Wohin gehen die rechtlichen und technischen Entwicklungen?
Tagungsband, erschienen im Juni 2010, ISBN 978-3-86009-087-9

Band 27
4. Rostocker Bioenergieforum
Zukunftstechnologien für Bioenergie
Tagungsband, erschienen im Oktober 2010, ISBN 978-3-940364-12-8

Band 28
Dirk Banemann
Einfluss der Silierung und des Verfahrensablaufs der Biomassebereitstellung auf den Methanertrag unter Berücksichtigung eines Milchsäurebakteriensiliermittel
Dissertation, erschienen im Januar 2011, ISBN 978-3-86009-087-9

Band 29
14. DIALOG Abfallwirtschaft MV
Abfall als Wertstoff- und Energiereserve
Tagungsband, erschienen im Juni 2011, ISBN 978-3-940364-18-0

Band 30
5. Rostocker Bioenergieforum
Tagungsband, erschienen im November 2011, ISBN 978-3-940364-20-3

Band 31
8. Rostocker Abwassertagung
Erhöhung der Effektivität von Abwasserentsorgungsanlagen
Tagungsband, erschienen im November 2011, ISBN 978-3-86009-120-3

Band 32
6. Rostocker Bioenergieforum
Tagungsband, erschienen im Juni 2012, ISBN 978-3-940364-27-2

Band 33
Ishan Machlouf
Untersuchungen zur Nitratelimination bei der Trinkwasseraufbereitung unter Berücksichtigung syrischer Verhältnisse
Dissertation, erschienen im März 2013, ISBN 978-3-86009-204-0

Band 34
Ralph Sutter
Analyse und Bewertung der Einflussgrößen auf die Optimierung der Rohbiogasproduktion hinsichtlich der Konstanz von Biogasqualität und -menge
Dissertation, erschienen im März 2013, ISBN 978-3-86009-202-6

Band 35
Wolfgang Pfaff-Simoneit
Entwicklung eines sektoralen Ansatzes zum Aufbau von nachhaltigen Abfallwirtschaftssystemen in Entwicklungsländern vor dem Hintergrund von Klimawandel und Ressourcenverknappung
Dissertation, erschienen im Mai 2013, ISBN 978-3-86009-203-3

Band 36
7. Rostocker Bioenergieforum
Tagungsband, erschienen im Juni 2013, ISBN 978-3-86009-207-1

Band 37
Markus Helftewes
Modellierung und Simulation der Gewerbeabfallaufbereitung vor dem Hintergrund der Outputqualität, der Kosteneffizienz und der Klimabilanz
Dissertation, erschienen im Oktober 2013, ISBN 978-3-86009-402-0

Band 38
Jan Stefan Riha
Detektion und Quantifizierung von Cyanobakterien in der Ostsee mittels Satellitenfernerkundung
Dissertation, erschienen im Oktober 2013, ISBN 978-3-86009-403-7

Band 39
Peter Helmke
Optimierung der Verarbeitungs-, Gebrauchs- und Entsorgungseigenschaften eines naturfaserverstärkten Kunststoffes unter Berücksichtigung automobiler Anforderungen
Dissertation, erschienen im November 2013, ISBN 978-3-86009-404-4

Band 40
Andrea Siebert-Raths
Modifizierung von Polylactid (PLA)für technische Anwendungen
Verfahrenstechnische Optimierung der Verarbeitungs- und Gebrauchseigenschaften
Dissertation, erschienen im Januar 2014 ISBN 978-3-86009-405-1

Band 41
Fisiha Getachew Argaw
Agricultural Machinery Traffic Influence on Clay Soil Compaction as Measured by the Dry Bulk Density
Dissertation, erschienen im Januar 2014 ISBN 978-3-86009-406-8

Band 42
Tamene Adugna Demissie
Climate change impact on stream flow and simulated sediment yield to Gilgel Gibe 1 hydropower reservoir and the effectiveness of Best Management Practices
Dissertation, erschienen im Februar 2014 ISBN 978-3-86009-407-5

Band 43
Paul Engelke
Untersuchungen zur Modellierung des Feststofftransports in Abwasserkanälen: Validierung in SIMBA®
Dissertation, erschienen im Februar 2014 ISBN 978-3-86009-408-2

Band 44
16. DIALOG Abfallwirtschaft MV
Aktuelle Entwicklungen in der Abfall- und Ressourcenwirtschaft
Tagungsband, erschienen im April 2014, ISBN 978-3-86009-410-5

Band 45
8. Rostocker Bioenergieforum, 19.-20. Juni 2014 an der Universität Rostock
Tagungsband, erschienen im Juni 2014, ISBN 978-3-86009-412-9

Band 46
Abschlussbericht Projekt CEMUWA – Climate protection, natural resources management and soil improvement by combined Energetic and Material Utilization of lignocellulosic agricultural WAstes and residues
Projektbericht, erschienen im September 2014, ISBN 978-3-86009-413-6

Band 47
8. Rostocker Baggergutseminar, 24.-25. September 2014 in Rostock
Tagungsband, erschienen im September 2014, ISBN 978-3-86009-414-3

Band 48
Michael Kuhn
Mengen und Trockenrückstand von Rechengut kommunaler Kläranlagen
Dissertation, erschienen im Oktober 2014 ISBN 978-3-86009-415-0

Band 49
8. Rostocker Abwassertagung, 10.-11. November 2014 in Rostock
Tagungsband, erschienen im November 2014, ISBN 978-3-86009-416-7

Band 50
Mulugeta Azeze Belete
Modeling and Analysis of Lake Tana Sub Basin Water Resources Systems, Ethiopia
Dissertation, erschienen im Dezember 2014 ISBN 978-3-86009-422-8

Band 51
Daniela Dressler
Einfluss regionaler und standortspezifischer Faktoren auf die Allgemeingültigkeit ökologischer und primärenergetischer Bewertungen von Biogas
Dissertation, erschienen im Mai 2015 ISBN 978-3-86009-424-2

Band 52
9. Rostocker Bioenergieforum, 18.-19. Juni 2015 in Rostock
Tagungsband, erschienen im November 2014, ISBN 978-3-86009-425-9

Band 53
Nils Engler
Spurenelementkonzentrationen und biologische Aktivität in NaWaRo-Biogas-fermentern
Dissertation, erschienen im September 2015 ISBN 978-3-86009-427-3

Band 54
Thomas Schmidt
Möglichkeiten der Effizienzsteigerung bei der anaeroben Vergärung von Weizenschlempe
Dissertation, erschienen im Oktober 2015 ISBN 978-3-86009-428-0

Band 55
Thomas Dorn
Principles, Opportunities and Risks associated with the transfer of environmental technology between Germany and China using the example of thermal waste disposal
Dissertation, erschienen im Dezember 2015 ISBN 978-3-86009-429-7

Band 56
Uwe Holzhammer
Biogas in einer zukünftigen Energieversorgungsstruktur mit hohen Anteilen fluktuierender Erneuerbarer Energien
Dissertation, erschienen im Dezember 2015 ISBN 978-3-86009-430-3

Band 57
17. DIALOG Abfallwirtschaft MV
Aktuelle Entwicklungen in der Abfall- und Ressourcenwirtschaft,
15. Juni 2016 in Rostock,
Tagungsband, erschienen im Juni 2016, ISBN 978-3-86009-432-7

Band 58
10. Rostocker Bioenergieforum, 16.-17. Juni 2016 in Rostock
Tagungsband, erschienen im Juni 2016, ISBN 978-3-86009-433-4

Band 59
Michael Friedrich
Adaptation of growth kinetics and degradation potential of organic material in activated sludge
Dissertation, erschienen im Juli 2016 ISBN 978-3-86009-434-1

Band 60
Nico Schulte
Entwicklung von Qualitätsprüfungen für die haushaltsnahe Abfallsammlung im Holsystem
Dissertation, erschienen im Juli 2016 ISBN 978-3-86009-435-8

Band 61
Ullrich Dettmann
Improving the determination of soil hydraulic properties of peat soils at different scales
Dissertation, erschienen im September 2016 ISBN 978-3-86009-436-5

Band 62
Anja Schreiber
Membranbasiertes Verfahren zur weitergehenden Vergärung
von feststoffreichen Substraten in landwirtschaftlichen Biogasanlagen
Dissertation, erschienen im Oktober 2016 ISBN 978-3-86009-446-4

Band 63
André Körtel
Entwicklung eines selbstgängigen statischen Verfahrens zur biologischen Stabilisierung und Verwertung organikreicher Abfälle unter extrem ariden Bedingungen für Entwicklungs- und Schwellenländer, am Beispiel der Stadt Teheran
Dissertation, erschienen im Oktober 2016 ISBN 978-3-86009-447-1

Band 64
Ayman Elnaas
Actual situation and approach for municipal solid waste treatment in the Arab region
Dissertation, erschienen im Oktober 2016 ISBN 978-3-86009-448-8

Band 65
10. Rostocker Abwassertagung, Wege und Werkzeuge für eine zukunftsfähige Wasserwirtschaft im norddeutschen Tiefland, 8. November 2016 in Rostock
Tagungsband, erschienen im November 2016, ISBN 978-3-86009-449-5

Band 66
Gunter Weißbach
Mikrowellen-assistierte Vorbehandlung lignocellulosehaltiger Reststoffe
Dissertation, erschienen im November 2016 ISBN 978-3-86009-450-1

Band 67
Leandro Janke
Optimization of anaerobic digestion of sugarcane waste for biogas production in Brazil
Dissertation, erschienen im Mai 2017 ISBN 978-3-86009-454-9

Band 68
11. Rostocker Bioenergieforum, 22.-23. Juni 2017 in Rostock
Tagungsband, erschienen im Juni 2017, ISBN 978-3-86009-455-6

Band 69
Claudia Demmig
Einfluss des Erntezeitpunktes auf die anaerobe Abbaukinetik der Gerüstsubstanzen im Biogasprozess
Dissertation, erschienen im Juli 2017, ISBN 9978-3-86009-456-3

Band 70
Christian Koepke
Die Ermittlung charakteristischer Bodenkennwerte der Torfe und Mudden Mecklenburg-Vorpommerns als Eingangsparameter für erdstatische Berechnungen nach Eurocode 7 / DIN 1054
Dissertation, erschienen im Juni 2017, ISBN 978-3-86009-457-0

Band 71
Sven-Henning Schlömp
Geotechnische Untersuchung und Bewertung bautechnischer Eignung von Müllverbrennungsschlacken und deren Gemischen mit Böden
Dissertation, erschienen im Juni 2017, ISBN 978-3-86009-458-7

Band 72
Anne-Katrin Große
Baggergut im Deichbau – Ein Beitrag zur geotechnischen Charakterisierung und Erosionsbeschreibung feinkörniger, organischer Sedimente aus dem Ostseeraum zur Einschätzung der Anwendbarkeit
Dissertation, erschienen im Juni 2017, ISBN 978-3-86009-459-4

Band 73
Thomas Knauer
Steigerung der Gesamteffizienz von Biogasanlagen durch thermische Optimierung
Dissertation, erschienen im Juli 2017, ISBN 978-3-86009-460-0

Band 74
Mathhar Bdour
Electrical power generation from residual biomass by combustion in externally fired gas turbines (EFGT)
Dissertation, erschienen im August 2017, ISBN 978-3-86009-468-6

Band 75
Johannes Dahlin
Vermarktungsstrategien und Konsumentenpräferenzen für Dünger und Erden aus organischen Reststoffen der Biogasproduktion
Dissertation, erschienen im September 2017, ISBN 978-3-86009-469-3

Band 76
Sören Weinrich
Praxisnahe Modellierung von Biogasanlagen
Systematische Vereinfachung des Anaerobic Digestion Model No. 1 (ADM1)
Dissertation, erschienen im März 2018, ISBN 978-3-86009-471-6

Band 77
18. DIALOG Abfallwirtschaft MV
Aktuelle Entwicklungen in der Abfall- und Ressourcenwirtschaft
Tagungsband, erschienen im Juni 2018, ISBN 978-3-86009-472-3

Band 78
12. Rostocker Bioenergieforum
Tagungsband, erschienen im Juni 2018, ISBN 978-3-86009-473-0

Band 79
Tatyana Koegst
Screening approaches for decision support in drinking water supply
Dissertation, erschienen im Juni 2018, ISBN 978-3-86009-474-7

Band 80
Liane Müller
Optimierung des anaeroben Abbaus stickstoffhaltiger Verbindungen durch den Einsatz von Proteasen
Dissertation, erschienen im September 2018, ISBN 978-3-86009-475-4

Band 81
Projektbericht Wasserwirtschaft
KOGGE – **Ko**mmunale **G**ewässer **G**emeinschaftlich **E**ntwickeln
Ein Handlungskonzept für kleine urbane Gewässer am Beispiel der Hanse- und Universitätsstadt Rostock
Projektbericht, erschienen im September 2018, ISBN 978-3-86009-476-1

Band 82
Adam Feher
Untersuchungen zur Bioverfügbarkeit von Mikronährstoffen für den Biogasprozess
Dissertation, erschienen im Oktober 2018, ISBN 978-3-86009-477-8

Band 83
Constanze Uthoff
Pyrolyse von naturfaserverstärkten Kunststoffen zur Herstellung eines kohlenstoffhaltigen Füllstoffs für Thermoplasten
Dissertation, erschienen im November 2018, ISBN 978-3-86009-478-5

Band 84
Ingo Kaundinya
Prüfverfahren zur Abschätzung der Langzeitbeständigkeit von Kunststoffdichtungsbahnen aus PVC-P für den Einsatz in Dichtungssystemen von Straßentunneln
Dissertation, erschienen im Dezember 2018, ISBN 978-3-86009-484-6

Band 85
Eric Mauky
A model-based control concept for a demand-driven biogas production
Dissertation, erschienen im Januar 2019, ISBN 978-3-86009-485-3

Band 86
Michael Kröger
Thermochemical Utilization of Algae with Focus on hydrothermal Processes
Dissertation, erschienen im Februar 2019, ISBN 978-3-86009-486-0

Band 87
13. Rostocker Bioenergieforum
Tagungsband, erschienen im Juni 2019, ISBN 978-3-86009-487-7

Band 88
12. Rostocker Abwassertagung
Tagungsband, erschienen im September 2019, ISBN 978-3-86009-488-4

Band 89
Philipp Stahn
Wasser- und Nährstoffhaushalt von Böden unter Mischkulturen und Trockenstress
Dissertation, erschienen im Juli 2019, ISBN 978-3-86009-489-1

Band 90
BioBind: Luftgestützte Beseitigung von Verunreinigungen durch Öl mit biogenen Bindern
Projektbericht, erschienen im September 2019, ISBN 978-3-86009-490-7

Band 91
Jürgen Müller
Die forsthydrologische Forschung im Nordostdeutschen Tiefland: Veranlassung, Methoden, Ergebnisse und Perspektiven
Habilitation, erschienen im Oktober 2019, ISBN 978-3-86009-491-4

Band 92
Marcus Siewert
Bewertung der Ölhavarievorsorge im deutschen Seegebiet auf Grundlage limitierender Randbedingungen – Ein Beitrag zur Verbesserung des Vorsorgestatus
Dissertation, erschienen im November 2019, ISBN 978-3-86009-492-1

Band 93
Camilo Andrés Wilches Tamayo
Technical optimization of biogas plants to deliver demand oriented power
Dissertation, erschienen im Februar 2020, ISBN 978-3-86009-493-8

Band 94
Robert Kopf
Technisches Benchmarking mit Standortqualifikationsstudie biochemischer Energieanlagenprojekte (Beispiel Biogas)
Dissertation, erschienen im Februar 2020, ISBN 978-3-86009-494-5

Band 95
14. Rostocker Bioenergieforum und 19. DIALOG Abfallwirtschaft MV
Tagungsband, erschienen im Juni 2020, ISBN 978-3-86009-507-2
DOI https://doi.org/10.18453/rosdok_id00002650

Band 96
Safwat Hemidat
Feasibility Assessment of Waste Management and Treatment in Jordan
Dissertation, erschienen im Juli 2020, ISBN 978-3-86009-509-6

Band 97
Andreas Heiko Metzing
Verdichtung von ungebundenen Pflasterdecken und Plattenbelägen - Untersuchungen zur Lagerungsdichte des Fugenmaterials
Dissertation, erschienen im Juli 2020, ISBN 978-3-86009-510-2

Band 98
Ying Zhou
Research on Utilization of Hydrochars Obtained by the Organic Components of Municipal Solid Waste
Dissertation, erschienen im November 2020, ISBN 978-3-86009-515-7

Band 99
Mathias Gießler
Ein prozessbasiertes Modell zur wirtschaftlich-technischen Abbildung von Abwasserunternehmen – Beispielhafte Anwendung für eine ländliche Region mit Bevölkerungsrückgang
Dissertation, erschienen im November 2020, ISBN 978-3-86009-516-4

Band 100
Dodiek Ika Candra
Development of a Virtual Power Plant based on a flexible Biogas Plant and a Photovoltaic-System
Dissertation, erschienen im Dezember 2020, ISBN 978-3-86009-518-8

Band 101
Thomas Zeng
Prediction and reduction of bottom ash slagging during small-scale combustion of biogenic residues
Dissertation, erschienen im Dezember 2020, ISBN 978-3-86009-519-5

Band 102
Edward Antwi
Pathways to sustainable bioenergy production from cocoa and cashew residues from Ghana
Dissertation, erschienen im Dezember 2020, ISBN 978-3-86009-520-1
https://doi.org/10.18453/rosdok_id00002818

Schriftenreihe Umweltingenieurwesen

Agrar- und Umweltwissenschaftliche Fakultät

Band 103

Umweltingenieurwesen • Wasserwirtschaft

Dissertation

Muhammad Waseem

Bd. 103

Integrated Hydrological and Mass Balance Assessment in a German Lowland Catchment with a Coupled Hydrologic and Hydraulic Modelling

Schriftenreihe

PROFESSUR Wasserwirtschaft

Universität Rostock Traditio et Innovatio

ISBN 978-3-86009-521-8
DOI: https://doi.org/10.18453/rosdok_id00002884

Universität Rostock Traditio et Innovatio