SPONSORED BY THE Federal Ministry of Education and Research

FONA Research for Sustainable Development BMBF

MuDak-WRM

Multidisciplinary data acquisition as the key for a globally applicable water resource management

Final Report

Karlsruhe, 28.02.2021

Karlsruher Institut für Technologie

UNIVERSITÄT KOBLENZ · LANDAU

EFTAS

HYDRON UMWELT und WASSERWIRTSCHAFT

52north exploring horizons

WUPPERVERBAND für Wasser, Mensch und Umwelt

TriOS Optical Sensors

MuDak-WRM -

Multidisciplinary data acquisition as the key for a globally applicable water resource management

Multidisziplinäre Datenakquisition als Schlüssel für ein global anwendbares Wasserressourcenmanagement

Final Report

Project duration: 01. April 2017 – 31. July 2020

Funding Budget: 2.639.748 €

Funding code: 02WGR1431

Project coordination:

Karlsruhe Institute of Technology, KIT
Institute for Water and River Basin Management
Department of aquatic environmental engineering (IWG-SWW)

PD Dr. Stephan Fuchs
Gotthard-Franz-Str.3, Geb. 50.31, 76131 Karlsruhe
Telefon: +49 721 608- 4 6199
Fax: +49 721 607 151
E-Mail: fuchs@iwg.uka.de
Web: http://isww.iwg.kit.edu

German project partners:

Partner	Funding Code
Institut für Wasser und Gewässerentwicklung (IWG), Karlsruher Institut für Technologie	02WGR1431A
Institut für Photogrammmetrie und Fernerkundung (IPF), Karlsruher Institut für Technologie	02WGR1431A
Institut für Umweltphysik (IUP), Universität Koblenz Landau	02WGR1431B
52°North - Initiative for Geospatial Open Source Software GmbH, Münster	02WGR1431C
Wupperverband, Wuppertal	02WGR1431D
EFTAS GmbH, Münster	02WGR1431E
HYDRON GmbH, Karlsruhe	02WGR1431F
TRIOS Mess- und Datentechnik GmbH, Rastede	02WGR1431G

Brazilian project partners:

Partner	
Companhia de Saneamento do Paraná (SANEPAR, Paraná Sanitation Company), Curitiba	
Universidade Federal do Paraná (UFPR, Federal University of Paraná), Curitiba	
Universidade Positivo, Curitiba	
Instituto das Aguas do Paraná, Curitiba	
Instituto Paranaense de assistência técnica e extensão rural (Paranaensisches Institut für ländliche Entwicklung), (EMATER), Curitiba	
Supported/ funded by:	
CAPES: Brazilian Higher Education Improvement Coordination, providing scholarships for Brazilian master and Ph.D. students, which were administrated via the graduate programs	
Araucária Foundation, (Fundação Araucária de Apoio ao Desenvolvimento Científico e Tecnológico do Estado do Paraná)	

The project on which this report is based, was funded by the Ministry for Education and Research, Germany under the funding code 02WGR1431. All responsibilities for the content remain with the authors.

Das diesem Bericht zugrundeliegende Vorhaben wurde mit Mitteln des Bundesministeriums für Bildung und Forschung unter dem Förderkennzeichen 02WGR1431 gefördert. Die Verantwortung für den Inhalt dieser Veröffentlichung liegt bei den Autoren.

Joint Final Report of the Sub-projects

Preamble:

This report does not aim to reproduce all created and generated results from the entire project period. The idea guiding this document is the necessity to consolidate central approaches, methods and results as well as the interpretation of these, to make them as easy accessible and usable for any potential reader or user.

Overview of German Authors

Institution/Company	Authors-/Project team
Institut für Wasser und Gewässerentwicklung (IWG), Bereich Siedlungswasserwirtschaft und Wassergütewirtschaft, Karlsruher Institut für Technologie (KIT)	PD Dr. Stephan Fuchs Dr. Stephan Hilgert Dr. Klajdi Sotiri Dr. Adrian Wagner
Institut für Wasser und Gewässerentwicklung (IWG), Bereich Wasserwirtschaft und Kulturtechnik, Karlsruher Institut für Technologie (KIT)	Prof. Franz Nestmann Dr. Frank Seidel Wendy Gonzalez Otero
Institut für Photogrammetrie und Fernerkundung (IPF), Karlsruher Institut für Technologie (KIT)	Prof. Stefan Hinz Dr. Andreas Schenk Jens Kern
Institut für Umweltphysik (IUP), Universität Koblenz Landau	Prof. Andreas Lorke Mayra Ishikawa
HYDRON GmbH, Karlsruhe	Dr. Ingo Haag Julia Krumm Katharina Teltscher
52°North - Initiative for Geospatial Open Source Software GmbH, Münster	Simon Jirka Eike Hinderk Jürrens Dr. Benedikt Gräler
EFTAS GmbH, Münster	Dr. Andreas Müterthies Dr. Kian Pakzad Dr. Nils Wolf
Wupperverband, Wuppertal	Karl-Heinz Spies Christian Malewski
TRIOS Mess- und Datentechnik GmbH, Rastede	Harald Rohr

Overview of international Authors

Institution/Company	Authors-/Project team
Companhia de Saneamento do Paraná (Sanepar)	Mauricio Bergamini Scheer
Universidade Federal do Paraná (UFPR, Federal University of Paraná)	Prof. Robson Armindo Prof. Tobias Bleninger Prof. Matheus Duraes Prof. Cristovao Fernandes Prof. Regina Kishi Prof. Heloise Knapik Prof. Michael Mannich Dr. Liege Wosiacki N. Barreto G. Bernadini Orides Golyjeswsky Gabriela Gomes Pedro Grochoki Luziadne Kotsuka Lediane Macron Jullyany Oliveira Gabriela M. Ono Javier Pérez Luciane Prado N. Ungaratti Diogo Varela

Inhalt

1. Zusammenfassung

Das Kernprodukt von MuDak-WRM war die Entwicklung von Modellen, Werkzeugen und Richtlinien zur Erleichterung des Managements von Stauseen, um eine gute Wasserqualität zu verbessern oder zu erhalten. Ein weiteres Ziel war die Vorhersage mittel- bis langfristiger Veränderungen der Wasserqualität in Stauseen, basierend auf Ansätzen reduzierter Komplexität und der Integration global verfügbarer Datenquellen, wie z.B. Satellitendaten. Der Schlüsselaspekt war, die Komplexität der zugrundeliegenden wissenschaftlich-mathematischen Ansätze und der benötigten Daten für die angepassten Modelle (LARSIM - Wasserhaushaltsmodell, MoRE - Emissionsmodell und Delft 3D - Wasserqualitätsmodell) zu reduzieren, um die Anwendung der Modelle mit vertretbarem Aufwand und in sinnvoller Weise in Regionen mit begrenzter Datenverfügbarkeit zu ermöglichen.

Die interdisziplinäre Forschungsgruppe auf deutscher Seite war ein Konsortium aus vier Forschungs- (Universität) und fünf Industriepartnern. Jedes Arbeitspaket wurde von einem oder zwei deutschen Partnern bearbeitet. Auf brasilianischer Seite waren drei Forschungs- und vier Industrie- bzw. öffentliche Partner in das Projekt eingebunden, so dass sich die Kompetenzbereiche spiegelten. Deutsche und brasilianische Partner wurden zusammengeführt, um den Wissensaustausch und die enge Zusammenarbeit bei den wissenschaftlichen und praktischen Aufgaben optimal zu ermöglichen.

Das Projektteam hatte sich zum Ziel gesetzt, das noch begrenzte Verständnis der Prozesse im Einzugsgebiet und im Stausee zu verbessern, dass bisher die Entwicklung vereinfachter Ansätze behindert. Die Projekthypothesen waren, dass Wasserqualitätsänderungen von Stauseen auf Langzeitskalen reagieren und dass Reaktionen auf sich ändernde Bedingungen (Inputs) modelliert und durch die Interpretation von Monitoringdaten verifiziert werden können. Ziel des MuDak-Teams war es, fortschrittliche Ergebnisse in praktischer Form zu liefern, die von internationalen Stauseebetreibern und Behörden genutzt werden können, um den Ist-Zustand eines Stausees zu beschreiben und die zukünftige Entwicklung der Wasserqualität unter Berücksichtigung bestimmter Managementoptionen vorherzusagen.

Das MuDak Projekt konnte erfolgreich die Erosions- und Transportprozesse im Einzugsgebiet mit den Verlandungstendenzen und Wasserqualitätsveränderungen im Stausee verknüpfen. Hierfür wurden Satellitendaten automatisiert ausgewertet und direkt als Eingangsparameter für das Erosionsmodel genutzt. Parallel wurde ein Wasserhaushaltsmodell implementiert, dass zum einen mit geringen Eingangsdatensätzen und größeren Datenlücken zurechtkam, zum anderen die Abflusskomponenten lieferte, die für die Eintragsmodellierung und die hydrodynamische Modellierung im Stausee nötig waren.

Untersuchungen im Stausee zeigten, dass die hohen Nährstoffeinträge nicht unmittelbar zu Algenblüten führten. Ein großer Teil des eingetragenen Phosphors bleibt im Sediment gespeichert. So ergibt sich aktuell keine Gefährdung der Wasserqualität in Bezug zur Wasseraufbereitung, jedoch können Umweltveränderungen zu einer Freisetzung dieses Phosphorspeichers führen. Insbesondere Sauerstoffmangel, der direkt mit der Anzahl der Tage, die der Wasserkörper geschichtet ist, zusammenhängt kann zu einem erhöhten Eintrag aus dem Sediment (internal loading) führen.

Es konnten zwei beispielhafte Maßnahmen identifiziert werden, um die Wasserqualität langfristig zu erhalten. Zum einen wurde berechnet, welche Flächen im Einzugsgebiet aufgeforstet werden müssten, um eine deutliche Reduzierung des Sediments und damit auch des Nährstoffeintrags zu erzielen. Hier würden bereits 3% der Fläche zu einer Reduzierung von 26% der jährlichen Sedimentmenge führen. Eine andere Maßnahme, ist die Konstruktion eines vorgelagerten „Pre-Dams“, einer Vorsperre. Dies ist in Deutschland üblich, in Brasilien, jedoch nur sehr selten der Fall. Hierdurch könnte ebenfalls eine deutliche Reduktion der Einträge in den Haupt See erreicht werden.

Verknüpft und verfügbar gemacht wurden die Projektdaten und insbesondere die real-time Wasserqualitätsdaten aus dem Stausee über ein Sensor Web. Es erlaubt nicht nur die Daten zu betrachten, sondern auch langjährige Vergleiche. Dazu wurde die Datenhaltung und Visualisierung für diverse Datentypen, wie Rasterdaten oder Vertikalprofile entwickelt. So hat der Stauseebetreiber, alle Informationen zur Beurteilung der aktuellen Situation aber auch der Entwicklung unmittelbar verfügbar.

Alle zentralen Erkenntnisse, Produkte und Ergebnisse sind in Form von Produkt Flyern dargestellt und zusammengefasst.

2. Summary

The core product of MuDak-WRM was to develop models, tools and guidelines to facilitate the management of reservoirs in order to improve or maintain good water quality. We also aimed on the prediction of medium to long-term changes of water quality in reservoirs, based on reduced complexity approaches and integration of globally available data sources, like satellite data. The key aspect was to reduce the complexity of the underlying scientific-mathematical approaches and the data required for the adapted models (LARSIM - water balance model, MoRE - emission model and Delft 3D - water quality model) to enable the application of the models with reasonable effort and in a meaningful way in regions with limited data availability.

The interdisciplinary research group on the German side was a consortium of four research (university) and five industry partners. Each work package was handled by one or two German partners. On the Brazilian side, three research and four industry or public partners were involved in the project, so that the areas of competence were mirrored. German and Brazilian partners were joined to optimally facilitate the exchange of knowledge and the close cooperation on the scientific and practical tasks.

The project team set out to improve the still limited understanding of processes in the catchment and the reservoir, which so far hinder the development simplified approaches. The project hypotheses was that water quality changes of reservoirs react on long-term scales and that reactions of changing conditions (inputs) can be modelled and verified by the interpretation of monitoring data. The MuDak team aimed to deliver advanced results in practical form, which can be used by international reservoir operators and authorities to describe the actual status of one reservoir and to predict the future development of water quality under the consideration of certain management options.

The MuDak project was able to successfully link the erosion and transport processes in the catchment area with the siltation tendencies and water quality changes in the reservoir. For this purpose, satellite data were automatically analyzed and directly used as input parameters for the erosion model. In parallel, a water balance model was implemented that, on the one hand, coped with small input data sets and larger data gaps, and, on the other hand, provided the runoff components needed for the input modeling and hydrodynamic modeling in the reservoir.

Studies in the reservoir showed that the high nutrient inputs did not directly cause algal blooms. A large part of the introduced phosphorus remains stored in the sediment. Thus, there is currently no threat to water quality in terms of water treatment, but environmental changes can lead to a release of this phosphorus storage. In particular, oxygen deficiency directly related to the number of days the water body is stratified can lead to increased input from the sediment (internal loading).

Two exemplary measures could be identified to maintain water quality over the long term. First, it was calculated which areas in the watershed would have to be reforested to achieve a significant reduction in sediment and thus nutrient input. Here, as little as 3% of the area would result in a 26% reduction in the annual amount of sediment. Another measure, is the construction of an upstream "pre-dam". This is common in Germany, but very rare in Brazil. This could also lead to a significant reduction of inputs into the main lake.

The project data and in particular the real-time water quality data from the reservoir were linked and made available via a sensor web. It allows not only to view the data, but also to make long-term comparisons. For this purpose, data management and visualization were developed for various data types, such as raster data or vertical profiles. Thus, the reservoir operator has all information for the assessment of the current situation but also the development immediately available.

3. Introduction

In many parts of the world water reservoirs are an essential source for drinking water supply and electricity production. Around 1.000.000 artificial water bodies and more than 100.000 larger reservoirs exist on the globe. They produce 20% of the global electricity and supply ~30% of the global irrigated agricultural area with water (ICOLD (International Commission on Large Dams). 1998–2009).
However, the installation and the operation of those is closely connected to a fundamental disruption of the river continuum. Reservoirs represent a sink for particulate matter as well as particle bound compounds like phosphorous, heavy metals and hydrophobic organic pollutants. Through the increase of the retention time in the reservoir in comparison to the free flowing river, the environmental conditions significantly change. One direct consequence is the accelerated eutrophication of the impounded water bodies.
Strong algae and cyanobacteria growth leads to severe, quality-related usage restrictions, especially for the extraction of potable water. Climate change may intensify the temporally unequal distribution of available water and therefore the regional water stress. At the same time, intensified agricultural activity and forest industry combined with increasing urbanization, lead to growing utilization pressure and phases of conflict prone water scarcity. Actual global examples illustrate the importance this topic.

The south east of Brazil with a high population density suffered a strong drought and water scarcity in 2015 and 2016 and once more since the end of 2019 until end of 2020. In the metropolitan region of Curitiba the drinking water reservoirs reached very low water levels with only 30% of storage volume left. Water shortages and power cutting were the consequences over months. During these phases some reservoirs showed strong water quality problems in connection with algae blooms. Comparable problems are well known for the rest of the world. In Germany, the increasing unequal distribution of rainfall (very dry summers) led to quantity and quality related water problems in the last three years (2018-2020) in drinking water reservoirs.
Such conditions, require long-term oriented, integrated management strategies, which consider water- and mass fluxes in catchments as well as the fundamental reactions in reservoirs. For this task, a range of models are available. However, the application of such performant software is often strongly limited in many regions of the world, due to a lack of input- and validation data in an adequate spatial and temporal resolution.
In many cases, the creation of catchment- and water monitoring parameters by conventional methodologies, is limited by temporal and financial restrictions. The reproduction of processes in catchments and in reservoirs in an adequate manner is, in these cases impossible.
Consequently, especially highly complex, and generally performant models are parametrized with default data. These models inevitably lose the regional context and therefore the necessary degree of information, which is needed for the derivation of effective management strategies.

The MuDak-WRM project focused on the tasks to

1. **Reduce the complexity** of model approaches (water balance model, emission model and water quality model) and therewith the related data demand.
2. Derive **central parameters** to describe the catchment- and water body characteristics based on globally available remote sensing data.
3. Develop **adapted methodologies** for an efficient onsite minimum monitoring.
4. Development of **strategies and measures** in cooperation with local/regional stakeholders to ensure long-term secure water supply.

In order to guarantee the success to the project, a tiered approach was chosen. The general methods and models were developed and tested at a well understood and monitored reservoir in Germany, the “Große Dhünntalsperre” operated by the Wupperverband. This reservoir, or exactly the pre-dam of this reservoir, served as a testing ground before the methods and models were transferred to Brazil. There, the Passaúna reservoir at the outer limits of the city of Curitiba was chosen as research subject due to the following criteria; the reservoir has a high importance for the drinking water supply for ca. 600.000 inhabitants, the water quality is still oligo-mesotrophic but with a tendency to deterioration, the catchment features strong anthropogenic influences and the operator of the reservoir, the company Sanepar showed active interest in the project cooperation and the project was accompanied by strong and highly motivated local partners from the academia and the authorities. These conditions summed up to a promising and interesting research area with a strong demand for a better reservoir-related process understanding and the development of measures to ensure good water quality in the future.

3.1. Background of reservoir management

Surface water bodies and especially water reservoirs are subject to a large variety of usage requirements (energy production, drinking water supply, irrigation, transportation, recreation, etc.). At the same time, they fulfill essential and unique environmental ecosystem functions. Both, the usability of water resources as well the ecosystem functions are threatened by the emissions from the catchment of a multitude of substances (nutrients, sediment, heavy metals,…). The anthropogenically increased input of nutrients (Phosphorous (P) and Nitrogen(N)) represents one of the main factors, why the water quality and related usage of waters is threatened (Conley et al. 2009; Schindler 2006), since these nutrients may cause algal blooms.

In this context, the relevant processes have been described very well (e.g. Likens und Gene 2010, Lake Ecosystem Ecology: A Global Perspective).

Sources of nutrients can be separated into diffuse and point sources (e.g. Figure 10). Even though, these terms are not used in a unified way, we define point sources as sources, which can be directly linked to on specific location of input to the river, e.g. waste water treatment plants. On the contrary, diffuse sources cannot be linked to one specific location of input to the river, e.g. surface runoff or erosion. The MuDak-WRM project focused mainly on the assessment, investigation and modeling of diffuse sources (erosion and surface runoff). The management of point sources relies strongly on the databases of local and regional authorities and can therefore, not be transferred to other regions by using technologies as remote sensing. However, the importance to control and manage point sources should not be generally degraded by this. Figure 1 illustrates a simplified overview of the relations between a reservoir and the catchment.

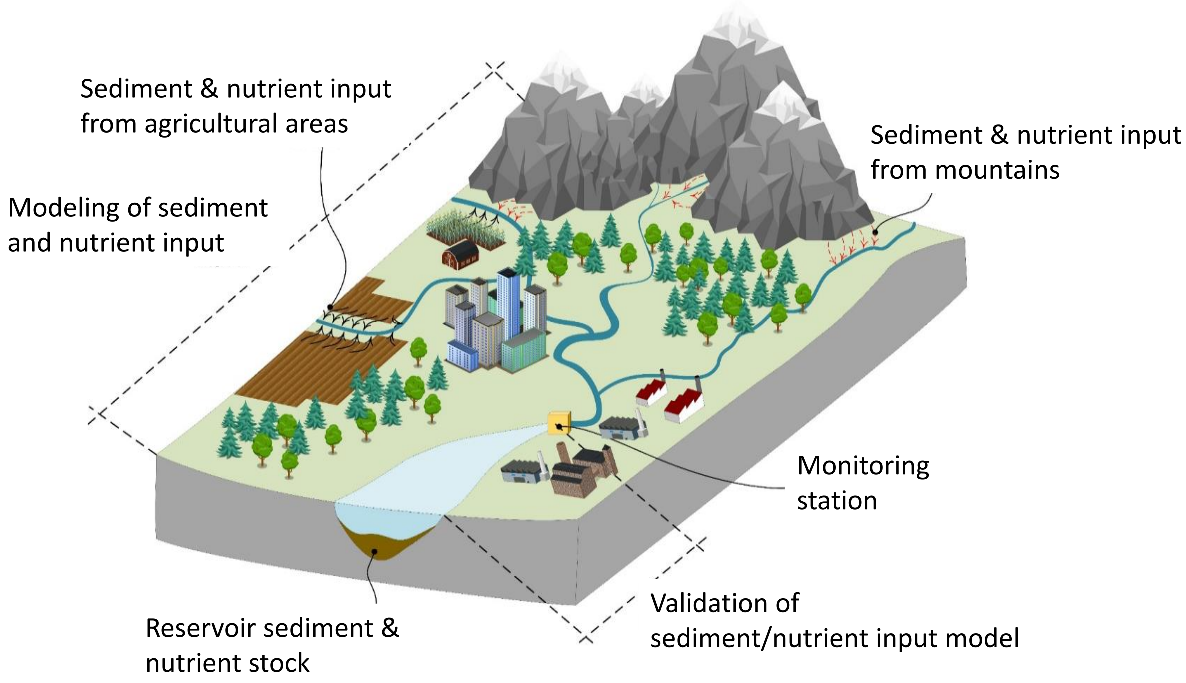


Figure 1: Illustration of the general transport and accumulation of sediment and nutrients from the catchment to the reservoir (adapted from Icograms).

The Catchment:

One central aspect for the protection of receiving water bodies (e.g. reservoirs) is the appropriate management of the corresponding catchments. A fundamental prerequisite to do so, is the quantification of the substance emissions, influenced by the different land uses. Most emissions from a catchment are seen as diffuse pollution, since no individual entrance location at the river can be identified. The estimation or the monitoring of these emissions is challenging and highly time demanding and costly. As substitutes for extensive field work, there are many models available globally, like SWAT, MIKE11, MoRE and CE-QUAL-W2. Most conceptual model approaches use partially spatially distributed parameter sets and empirical quantification approaches. The hydrological components are based on the HRU approach (Hydrologic Response Unit, Flügel 1996). All these models use material balance approaches calculated for grid cells or hydrological units. This feature allows for large-scale application in contrast to process-oriented model approaches. Application limitations for the above-mentioned and other empirical models arise in part from the fact, that the model approaches used are in part only modifiable to a limited extent and, if so, then generally only by intervening in the program code. The emission model MoRE (Fuchs et al. 2010), which was the starting point for the development in this project, solves this problem by a model implementation, in which, all input data and calculation approaches are managed in an open source database and are freely editable without programming knowledge (https://isww.iwg.kit.edu/MoRE.php).

An essential component of substance input modeling is the adequate representation of the water balance and its components. The water budget model LARSIM (LARSIM-Entwicklergemeinschaft 2016), which is widely used in water management practice, can meet these requirements. The model, which was developed by Bremicker (2000), has been continuously developed over the past 20 years, especially for operational flood forecasting (Luce et al. 2006) for water temperature forecasting (Haag and Luce 2008), for low-flow management (e.g., Varga and Haag 2013), and for optimization of reservoir controls (Holle 2009) in Germany, Luxembourg, Switzerland, Austria, and France (Bremicker et al. 2013).

The modular structure of the model allows for an area-specific setup, that uses the geospatial data available in the respective area (e.g., elevation model, vegetation mapping, soil data, etc.). Both, the water balance model and the substance emission model require data on catchment characteristics. Land use, topography, land cover, etc. are examples. This information is not available everywhere in adequate quality, and can terrestrially only be collected over larger catchments with very high effort, which is why modern remote sensing methods are of great importance. They do not only deliver the necessary information to run catchment-based models, but nowadays, remote sensing increases significantly the temporal resolution of this information. This fact represents a fundamental step forward for the precise assessment of catchment processes and therefore, the planning of catchment related management options. Within the MuDak project developments were conducted to investigate the full chain from remote sensing, over data processing to a reduced complexity water balance model and the implementation of a higher temporally resolved emission model, towards more precise measures to be implemented in the catchment.

The River:

Within the focus of the MuDak project, the Passaúna river or the tributaries of the Große Dhünn reservoir, were reduced to the function of transporting water, sediment and other chemical compounds to the reservoirs. The rivers were understood as transport vectors without relevant retention or degradation capacities. In the case of the MuDak project the focus parameters were total suspended solids (TSS), total Phosphorous and dissolved (ortho) Phosphate. All parameters, are supposed not to change in terms of mass balance within the time steps of the catchment models (moths to years), therefore any river-related processes were left out of investigation. It was assumed that “what enters a river, reaches the reservoir”:

In terms of validation and plausibilisation of the catchment processes, the river was used to better understand the transport processes going back to the catchment behavior. No further investigations on the rivers were done, due to the fact that the project team deemed rivers to be the least efficient point to implement measures for the protection of reservoir water quality. However, a minimum set of input data (discharge, temperature, sediment transport, etc.) is necessary to understand the fundamental processes in the reservoirs.

The Reservoir:

Safeguarding the use of water resources includes not only proper catchment management but also options within the water body itself, such as artificial mixing to reduce cyanobacterial blooms (van der Veer et al. 1995, Visser et al. 1996) or varying the depth and timing of abstraction for drinking water production (Fontane et al. 1981; Hayes et al. 1998). A prerequisite for the implementation of these and other options for action is that in-lake processes that significantly determine the fate and conversion of input nutrients, are known and incorporated into decision-making processes.

While the interactions of physical transport and nutrient (Chung et al. 2014; Hamilton and Schladow 1997) and algal (Liu et al. 2012; Peeters et al. 2007; Sverdrup 1953) dynamics in density-stratified lakes and reservoirs have been extensively studied, particularly using coupled hydrodynamic and ecological models, the coupling of in-lake process dynamics with the dynamics of nutrient inputs from the catchment represents mostly uncharted scientific territory. Current efforts to fill this gap in terms of both process understanding and catchment management strategies often aim to establish high-resolution and costly monitoring networks (Rinke et al. 2013). Approaches to data reduction and predominant use of remote sensing data to describe in-lake nutrient fluxes and resulting water quality have been poorly studied.

Most water quality parameters can be directly or indirectly linked to the amount and composition of sediment reaching one reservoir. Additionally, the siltation of the reservoir is a technical problem, which affects most reservoirs to a certain extend. Therefore, this project put much effort in the investigation of sediment input dynamics, sediment distribution inside the reservoir as well as sediment quality and related water quality aspects.

The project included the challenge to make best possible use of available remote sensing techniques (drone-based and satellite-based) as well as automated high-resolution in-situ sensors for water quality validation.

Inland waters are considered to be optically complex because their reflectance is usually influenced by several parameters simultaneously, such as suspended sediments, algae, and coloring organic compounds. Nevertheless, spectrally high-resolution sensors can adequately detect and map the catchment- and season-specific distribution of these water quality parameters in surface waters. Drone-based multi- and hyperspectral measurement techniques have already been exemplarily tested for water applications (Honkavaara et al. 2013; Su and Chou 2015). In addition to the close distance to the target and the lower cost, the main advantage is the high flexibility. Until now, the number of simultaneously collected in-situ water samples was often the limiting factor due to the complicated tuning of satellite overflights and their cloud dependence. To determine water parameters, superimposed effects of wavelength-specific absorption and scattering of the various optically active constituents must be spectrally separated and quantified. We planned and optimized our activities to combine results from field campaigns, lab analysis, drone flights and satellite overflights as good as possible in order to bridge the scaling gap from point measurements (representing some cm^2) to spatial measurements (representing hacres).

Data infrastructure

Water resource management is a multidimensional task that requires a fundamental understanding of processes and extensive input data. Consistent management and provision and linking of heterogeneous data sets thus becomes an essential part of any project. While spatial information can be exchanged and processed in a largely standardized way by means of web-based spatial information infrastructures (SII), measurement data with heterogeneous sources require software systems that use open interfaces for e.g. time-based datasets (e.g. OGC SWE; Bröring et al. 2011). The reliability of this technology has already been comprehensively proven in a number of scientific studies (Resch et al. 2009; Spies and Heier 2008). In this context, the Wupperverband successfully uses a Sensor Web data infrastructure based on OGC SWE (Spies and Heier 2010).

In addition to the secure provision of harmonized and quality-assured data, the integration of different sensors or measurement data into a central infrastructure offers the advantage that e.g. the different sensor data can be comparatively integrated into the modeling approaches. This is a prerequisite for the operational use of the models.

In addition to the scientific and technical aspects, the uniform and transparent storage of diverse measurement data is the foundation for long-term use of high-quality data sets.

3.2. Project Objectives & Project Implementation

The overall objective of the MuDak-WRM project was the investigation of water quality related processes in drinking water reservoirs and the development of simplified environmental models reproducing the most relevant compartments (catchment emissions, water balance and water quality).

These models are fed by innovative and long-term monitoring in the catchment as well as inside the reservoir. In order to substitute local, in-situ information with remote sensing data, several approaches from multispectral and radar data to derive input information, were followed.

All work packages, dealing with modeling, had the goal to reduce the complexity and the data demand of the single model parts, in order to facilitate a global transfer of the models to regions with limited data availability.

The work packages, which worked on data acquisition and monitoring addressed the task, next to the provision of input data for the modeling and model validation, to develop minimum monitoring approaches. Which means, that the high-resolution data obtained, was analyzed to identify most significant monitoring patterns in time and space. Where to measure what, how often? – and to still prevail the necessary level of information needed to feed the models. A selective and optimized monitoring is needed, to bundle available budgets and efforts by the responsible authorities or companies in charge. The more limited monitoring budgets are, the better should be the selection of timing and locations of monitoring in the catchment, at the river or within the reservoir. Additionally, a discussion of most relevant parameters to follow and control the quality status of a reservoir, was conducted.

The MuDak project set out to produce usable products or transform preliminary scientific results into usable products, applications or guidelines for reservoir operators, authorities and scientists. These results are summarized in the form of Flyers (see chapter 3.4 Introduction of the work packages

The results of the MuDak-WRM project are presented and sorted by work packages (WP) respectively by topic, independent of the affiliation of the involved researchers. Most WP were conducted by mixed teams from Germany and Brazil, as well as from universities and industry partners. Figure 2 shows an overview of the project components and related work packages. Basically, four working areas were defined beforehand of the project: 1. The water body, 2. The catchment, 3. Remote sensing and 4. Sensor Web and Data interoperability.

The background and objectives of the single work packages are explained in detail in chapter 4.4.

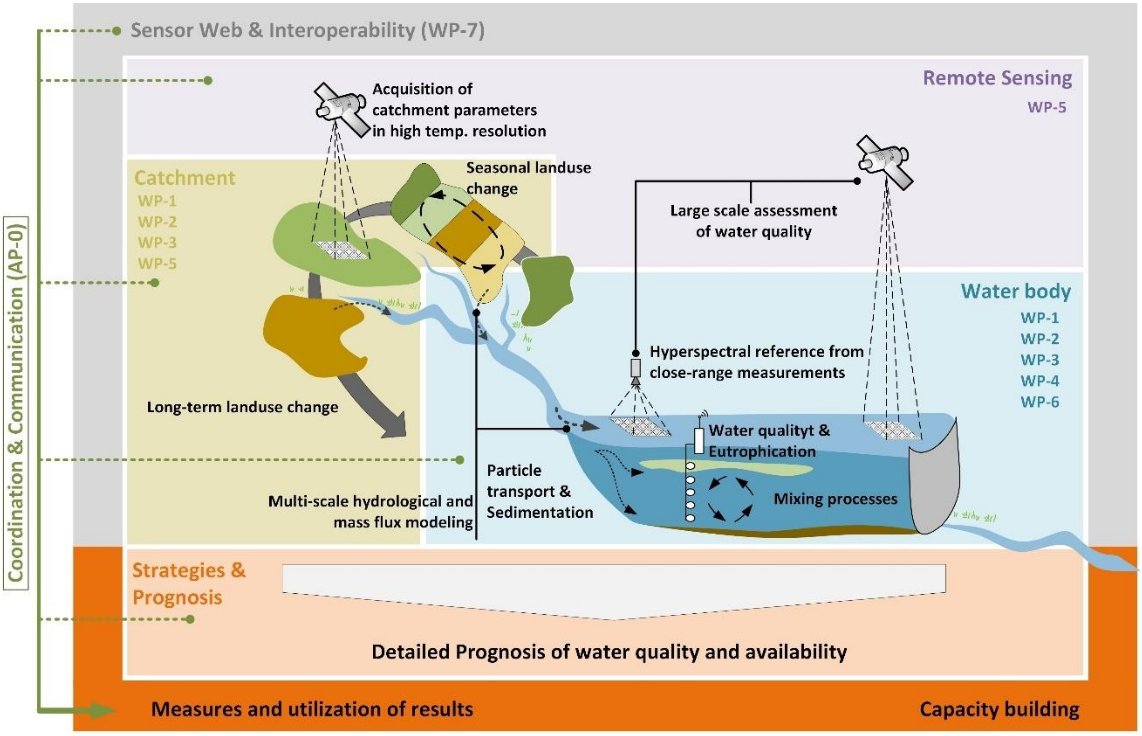


Figure 2: Overview of project compartments and related work packages.

4. Project Insights

4.1. Planning and operation of the project

The general structure, procedure and planning of the project in order to solve the addressed challenges and to answer the scientific and praxis-related questions, the project consortium was split into three methodological-technical parts. Three work packages (WP 1, 5, 6) produced primary data from field measurements, which was passed on for in-situ verification and the validation of models. Four work packages adapted a water balance model (WP 2) (LARSIM), an substance emission model (WP1) (MoRE) and a hydrodynamic model (WP 3) combined with a water quality model (WP6) (Delft 3D) for the case study and derived approaches for a reduction of complexity (Figure 3). In order to reduce the complexity and data demand, the models were first developed to run with the best possible input data. From this stage on the input data was reduced in terms of temporal and spatial resolution as well as measurement quality itself. Unnecessary model parts were excluded from the calculations to increase the performance and reduce complexity. The aim was to find the minimum data demands for the models and to still reproduce the correct dimension of input mass fluxes (sediment and phosphorous), correct river flow into the reservoir as well as reproduction of stratification days, water temperature and critical water quality status of the reservoir.

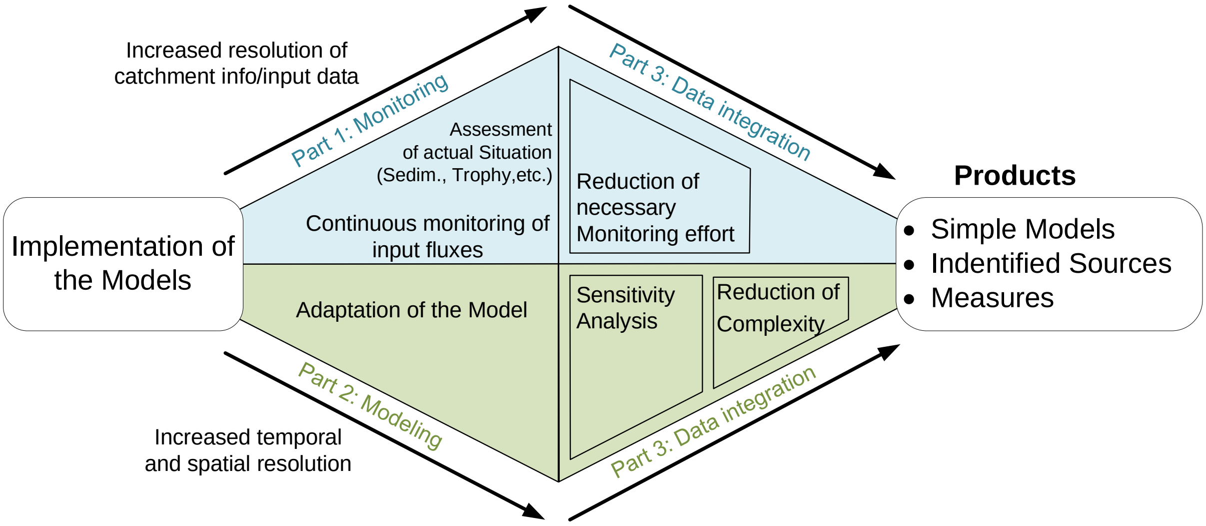


Figure 3: Methodological project approach for model complexity reduction.

The third part (WP 7) worked on the integration, storage and visualization of complex and diverse environmental project data. A data exchange and standardization protocol was developed between all project partners. This allowed the project team to easily exchange data without formatting conflicts with a wide range of characteristics and including essential metadata. These encompassed different spatial aspects like point (water sample), linear/transect (boat-based sensors), vertical (water column) and raster data (satellite). Additionally, different temporal aspects were included like singular measurements (campaign-based), single time series (multiple measurements campaign-based) and (real-time) continuous measurements (permanent installed sensor data). All types of data were stored on a central server and were linked to the only web client.

The principal workflow was developed along three reservoir case studies (Figure 4). The first region, Große Dhünn reservoir (Wupperverband), was used as a “best case” scenario in terms of data availability and good accessibility. The developed models were transferred to Passauna reservoir (Sanepar), where a consistent, long time series of water quality data and catchment information was missing. After further development of approaches and complexity reduction a final simplified model version was produced. This model will be applied by the reservoir operator in the Piraquara 2 catchment to predict water quality changes of the reservoir. By the transfer to a new catchment the functionality as well as the transferability of the product can be assessed.

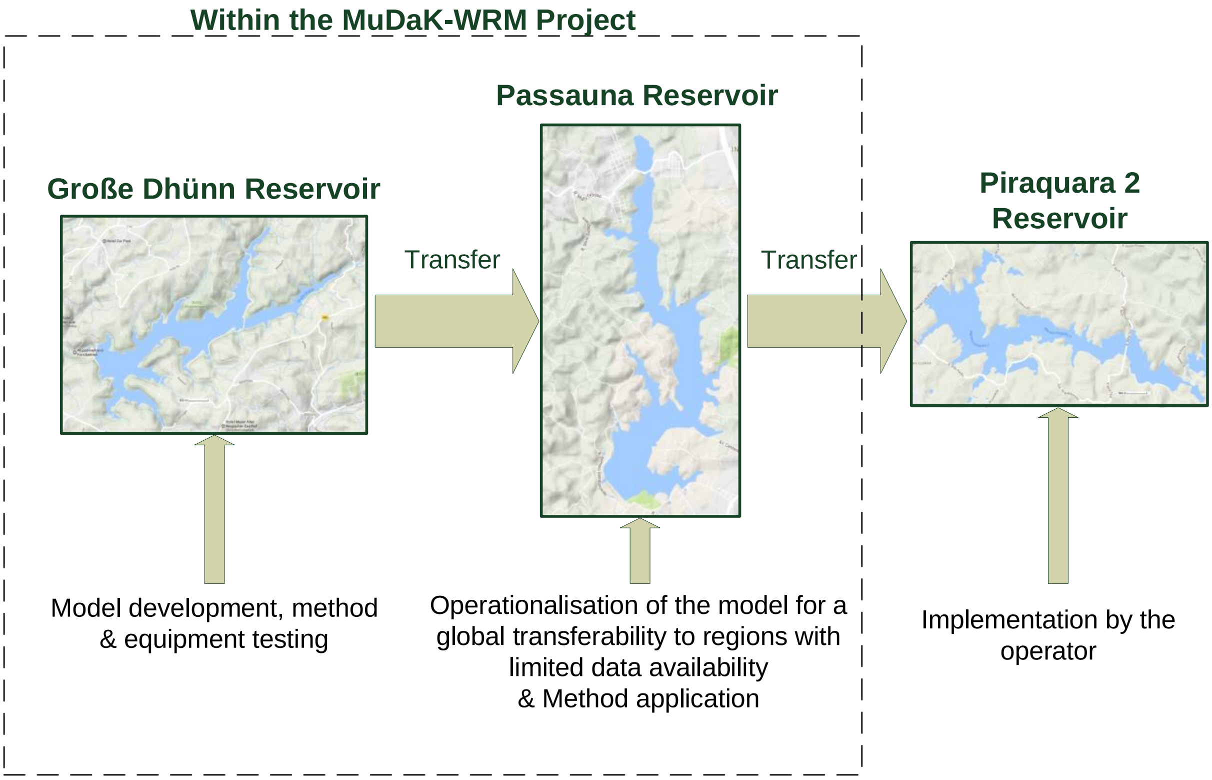


Figure 4: Method- and model development and transfer of project results

Monitoring encompasses activities in the catchment like continuous water sampling at the river inflow to assess the particle and nutrient flux to the reservoir, sediment and soil sampling and the analysis of satellite imagery to retrieve land use and land cover change. Reservoir monitoring includes real-time water quality measurements on a platform (Figure 5) at the water intake in Passauna reservoir combined with monthly water sampling campaigns. Additionally an upward looking ADCP gives insights in internal flow velocities and flow directions. The detailed investigation of in-lake processes is complemented by campaign-based drone flights to better understand the spatial distribution of quality parameters (e.g. turbidity and chlorophyll conc.) and to bridge the information to the satellite imagery.

Figure 5: Measurement platform close the water intake of Passaúna reservoir.

4.2. Study Areas

The scientific and technical objectives of this project were reached through the combination of two investigation areas at which different core parts of the project were conducted. The Große Dhünntalsperre served as a testing area for field monitoring and model development. The Große Dhünntalsperre catchment covers an area of 89 km^2 and 90% of the catchment is covered by forest and pasture land as shown in (Figure 6). The Dhünntalsperre is protected by 22 pre-dams at the inflows of entering rivers.

The largest part of the field activities, however, was conducted in the catchment and at the water body of the Passaúna reservoir. The hydrological catchment of the Passaúna river is located in the Primeiro Planalto Paranaense, between parallels 25 ° 15 '–25 ° 35' South and meridians 49 ° 25 '–49 ° 20' West. The hydrological catchment partly covers the municipalities of Curitiba, Araucaria, Campo Largo, Campo Magro,and AlmiránteTamandaré and is a sub-basin of the Iguaçu River. The region is classified as Cfb (temperate oceanic climate) according to the Koppen climate classification. The mean temperature during summer is 22°C, while the mean temperature in the winter months is 18°C (marcon et al. 2019). The average yearly precipitation in the watershed is1650 mm. The catchment has an area of approximately 150 km^2 that creates an average yearly inflow of 2 m^3/s for the Passaúna reservoir. The Passaúna river composes 65.6% of the overall inflow into the reservoir, followed by the Ferraria river (6.9%), the Eneas river (3.6%), the own reservoir area (5.9%) and the runoff created from the small sub-basins surrounding the reservoir (18.0%) (Carneiro et al. 2016). Most of the catchment is covered by forest (43%) and agricultural area (26%) (Figure 6). Despite having been an environmentally protected area since 1994, a yearly increase of 2.25% (Instituto Brasileiro de Geografia e Estatística 2011) has been recorded in the population of the catchment (2010 population 66,000 inhabitants). Sanitation facilities are mostly available, but still a part of the untreated sewage enters the river system from the semi-formal urban areas.

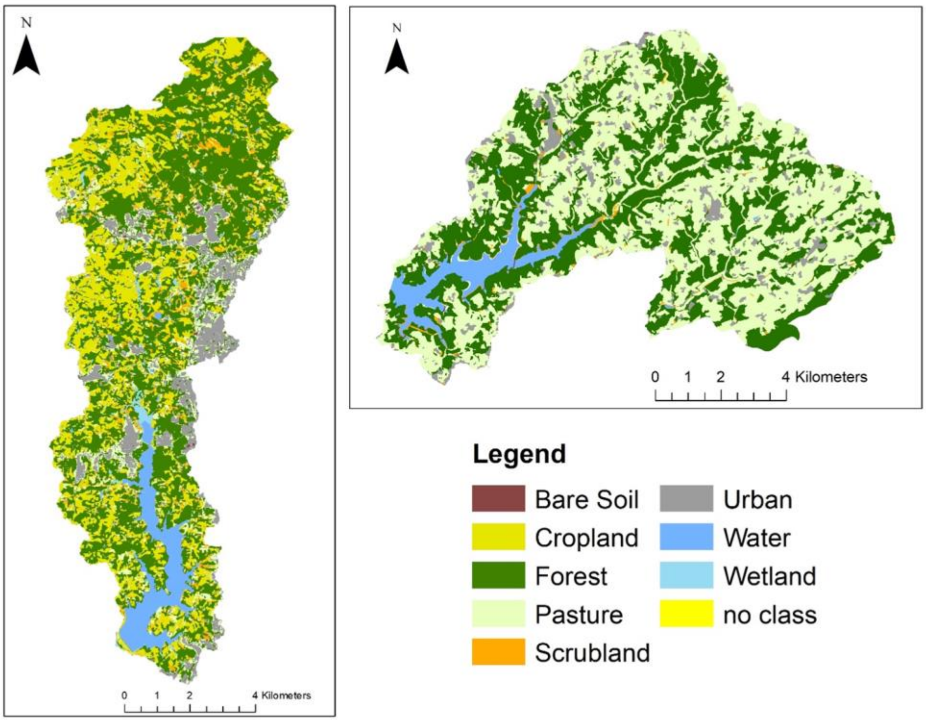


Figure 6: Land use maps of the Große Dhünntalsperre and Passaúna reservoir.

The three reservoirs were selected for the implementation of the project for the following reasons:

- The **Große Dhünn reservoir** represents a highly parameterized environment due to the optimal data availability through long-term measurements and a comprehensive database of the Wupperverband, in which the measurement concepts and models can be tested and adapted under perfect conditions. This is an important step in the targeted reduction of the complexity and data requirements of the models.

- The **Passaúna reservoir** was selected because it is ideally suited for the described investigations and model development for several reasons. First, eutrophication of the reservoir has progressed to the point where direct action is needed in the coming years, but second, eutrophication has not yet manifested to the extent that targeted actions would not show effects. In addition, Passauna with the characteristics summarized in Table 1 represents the majority of the globally existing reservoirs, which is relevant with regard to a transferability of the products to be developed. The catchment area of Passauna is very heterogeneous with a strong urban influence, which allows in particular the development of the methods in WP-5 and 6 as well as the models from WP-1, 2 and 3.

- **Piraquara 2** was chosen as an exemplary reservoir in the direct surroundings of the city of Curitiba. It is also managed by Sanepar, however, in contrast to the Passaúna reservoir it shows strong eutrophication symptoms already. Therefore, it is a suitable transfer region to implement the developed models, to apply measurement or monitoring strategies or if the data basis allows, plan and implement mitigation measures (Figure 4). It was planned that the transfer of the project results will be supported by the MuDak-team, but needs to be conducted by the Sanepar itself. Therefore, the application of findings and measures at Piraquara 2 was not seen as an incremental part of the funded project, it represents a clear perspective where the obtained results can be applied in the close future.

Table 1: Summary of the most important parameters of the project reservoirs.

	Große Dhünn reservoir	**Passaúna reservoir**
Area	4,4 km²	9 km²
Dam height	53 m	20 m
Volume	81 Mil. m³	48 Mil. m³
Catchment	89 km²	150 km²
Age	33 years	30 years
Purpose	Drinking water supply (500.000 EW)	Drinking water supply (650.000 EW)
Status	oligotrophic	Oligo to mesotrophic

4.3. Cooperation

The project success based on the close and intense cooperation with Brazilian partners. To solve the interdisciplinary tasks outlined above, a consortium of four research and five industrial partners was brought together on the German side. All the competencies required for successful completion of the project are represented in this consortium. Each work package is being handled by one or two German partners. On the Brazilian side, two research partners (universities) and three industrial or public partners are involved in the project, so that the areas of competence are mirrored. Funding for the Brazilian side was provided by inkind contributions from all Brazilian partners, as well as by complementing research funds from:

- **CAPES:** Brazilian Higher Education Improvement Coordination, providing scholarships for Brazilian master and Ph.D. students, which were administrated via the graduate programs
- **Araucária Foundation,** (Fundação Araucária de Apoio ao Desenvolvimento Científico e Tecnológico do Estado do Paraná)

It was prepared over a long time period by smaller preceding projects, which helped to intensify the cooperation and to build a high degree of trust. The core team of the international cooperation shown in the MuDak project, worked more than 10 years on the cooperation before the project started.

The partners, who participated in the project, are listed here:

- **Companhia de Saneamento do Paraná** (SANEPAR, Paraná Sanitation Company), Curitiba
- **Universidade Federal do Paraná** (UFPR, Federal University of Paraná), Curitiba

  PPGERHA (Graduate Program on Water Resources and Environmental Engineering, Graduiertenprogramm für Wasser- und Umweltingenieurwesen), Curitiba

  PPGEA (Graduate Program on Environmental Engineering)

  PPCGC (Graduate Program for Geodetic Sciences)

  - Depto. Engenharia Ambiental **(DEA)**
  - Depto. de Hidráulica e Saneamento **(DHS)**
  - Depto. da Geomatica **(DG)**
  - Depto. Solos e Engenharia Agrícola **(DSEA)**
- **Universidade Positivo**, Curitiba

PGAMB (Graduiertenprogramm für Umweltwissenschaften)

- **Instituto das Aguas do Paraná**, Curitiba
- **Instituto Paranaense de assistência técnica e extensão rural** (Paranaensisches Institut für ländliche Entwicklung)**, (EMATER)**, Curitiba

Especially, the long lasting and intense cooperation between KIT and UFPR was a central part of the success of the complex and challenging work packages. All German partners are very thankful to the professors at UFPR, namely Prof. Bleninger, Prof. Kishi, Prof. Fernandes, Prof. Centeno, Prof. Knapik and Prof. Detzel, Prof. Robson Armindo, Prof. Matheus Duraes and their great researchers and lab teams. The MuDak-team is in debt to the overall active Postgraduate Program in Water Resources and Environmental Engineering (http://www.prppg.ufpr.br/ppgerha/en/) based at the UFPR.

The full MuDak team is shown in Figure 7.

Figure 7: MuDak-team at the Kick-off workshop. In the background is Passaúna reservoir.

Altogether, 17 PhD students were involved in the MuDak project. An even higher number auf Bachelor-, Master- and study projects were successfully conducted on both, the German and the Brazilian side. For PhD students a sequence of research stays in Germany and Brazil lead to three double-PhD degrees, underlining the success of sustainable cooperation and the importance of international research activities.

Figure 8: MuDak PhD students on a workshop at Passaúna reservoir in 2017.

The operating company of Passaúna reservoir, Sanepar, is the 4th largest water supplier in Brazil. The close cooperation within this project allowed for a direct exchange of information, data and also to develop the project products close to the need of the company. A sequence of schooling events for theory and in praxis were conducted. Joint field trips together with lectures were used for capacity building. The handling of equipment, processing of data and general knowledge on reservoir management were exchanged. The excellent cooperation manifested itself in the joint purchase of a new research vessel, which served as an operation base during all field campaigns (Figure 9). The vessel will facilitate research activities in the future and further strengthen the cooperation between Sanepar and university researchers.

Figure 9: Manifestation of the cooperation between the German partners and Sanepar - a joint research vessel.

4.4. Introduction of the work packages

WP 1 – Emission modeling and validation

Work package 1 was separated into two parts (Catchment box and reservoir box, **Fehler! Verweisquelle konnte nicht gefunden werden.**) Part one focused on activities in the catchment, including the development of a low-complexity emission model, based on the MoRE model already available for German and some European catchments, soil sampling, river sediment sampling and catchment visits to better understand structures of semi-urban areas. The second part of the WP focused on the validation of the modeling results. This included long-term monitoring activities in the river, upstream of the inlet to the reservoir. Additionally, extensive sediment and sedimentation investigations inside the reservoir were conducted. These again, were split into the assessment of the incoming and settling sediment and the detection and investigation of the already accumulated sediment on the ground of the reservoir.

The main objectives of WP 1 were

Catchment:

- Reduction of model complexity of the MoRE model.
    - Reduction of structural complexity
    - Reduction of data demand
- Sampling of soil samples as input for the erosion modeling
- Sampling of river sediment samples to compare Phosphorous content in the sediment with the sources and the transported material
- Investigate potential point sources e.g. settlements, septic tanks etc.

Reservoir:

- Measure the actual bathymetry and derive the volume-water level curve
- Assess the sediment thickness and overall sediment mass, calculate the annual siltation rate
- Investigate internal sediment transportation processes (density currents)
- Investigate sediment composition (organic matter, nutrient content)
- Validate modeled sediment and nutrient input

Both WP parts together aimed on the development of adapted measures to improve or protect the current status of water quality.

WP 2 – Water balance model:

The basic objective of the work package 2 (WP 2) was to develop and provide a generally applicable and transferable water balance model as a central building block for watershed and surface water body management. On the one hand, this model can be used alone and independently for water quantity management. On the other hand, it can be integrated as a central water balance module in a comprehensive management model for water quantity and water quality. In the course of development, the effects of reduced data availability and model complexity were also analyzed in order to define minimum standards and ensure general applicability.

The main scientific objectives of WP 2, as part of the overall project, are as follows:

- Develop methods to quantify the effect of reduced data availability and model complexity on the applicability and robustness of results on water balance and runoff formation (diffuse matter discharge).
- Scientifically justified reduction of model complexity and data requirements to improve global transferability
- Improved understanding of the impact relationships between runoff formation and the resulting diffuse matter discharge (in collaboration with WP1).

In addition, the following primary technical objectives were pursued:

- Provide a generally applicable and transferable water balance model as a central building block of management planning.
- Use of globally available remote sensing data for model development and validation.
- Provision of concretely applicable models (in the context of the overall management model) for the Wupper catchment (Grosse Dhünn) and Passaúna (Brazil).
- Determination of the minimum technical requirement for the use of water balance models in the context of management planning.
- Clarification whether already existing LARSIM water balance models can be used for management planning, or which adaptation may be necessary.
- Development of efficient interfaces to spatial input data for model setup (especially remote sensing data) and to the emission model MoRE to enable effective calculation of management scenarios.

WP 3 – Hydrodynamic and sediment transport modeling

In AP 3, a flow and sediment transport model was set up for Passaúna reservoir, which represents the flow characteristics as well as the relevant physical fine sediment and basic water quality processes in the reservoirs on the basis of hydrological (AP 2) and morphological (AP 1) measurement data. The goal was to simulate both, the stream flow in the reservoir as well as the sedimentation processes of the fine particles carried in from the river. Within the framework of the modeling, comparative calculations at the Große Dhünn reservoir (pre-dam) in Germany were conducted beforehand.

In connection with the modeling, it was investigated which model complexity and model approaches or which input data basis are necessary to represent the relevant fine sediment processes in a physically plausible and correct way.

The main objectives of WP 2 were:

- The numerical modeling of the finesediment transport in the reservoirs, in particular the transport and deposition of fine particles, considering the relevant physical sub-processes.
- The simulation of density currents due to density differences during inflow into standing water (e.g. caused by different temperatures or suspended sediment contents over the flow depth)
- Identification of the influence of wind and temperature on the hydrodynamics and sediment transport in the reservoir.
- Modeling of the stratification and mixing processes in the reservoirs

The goal of the set up numerical model (Delft 3D) was both, to develop a systems understanding of the complex fine sediment and water quality processes in the reservoir and to quantify the effects of reduced data availability and model complexity on computational results.

WP 4 – Close range remote sensing

A qualitative and quantitative assessment of terrestrial material discharge potentials into reservoirs can be significantly supported by innovative close-range remote sensing methods. The advantage of imaging remote sensing compared to in-situ measurements is mainly the extensive data acquisition and in the case of satellite data the global availability. In this project, a multimodal sensor system will be integrated on a compact UAS to map inflows, their inputs and the distribution of constituents within the reservoir. The assembled system will be integrated into a concept for autonomous and continuous monitoring of reservoirs. The aim of autonomous and extensive monitoring of water quality parameters by means of close-range remote sensing entails three main scientific challenges, which will be addressed in this subproject: Parameter estimation of e.g. suspended sediments and chlorophyll, geocoding of acquired image data over water, scale jump between the methods (in-situ measurements, close-range remote sensing, satellite remote sensing).

Of particular interest for the detailed analyses were:

- inflows and their (sediment) inputs into the reservoir, especially episodic inputs after heavy rain events.
- distribution of turbidity, chlorophyll and temperature at the surface of the reservoir.

This WP aimed on the following points

- Using drone-based hyperspectral sensors for water quality parameter measurement
- Using hyperspectral boat-based sensors for the measurement of spatially changing surface water quality parameters (turbidity, chlorophyll-a).
- To enable the scale transition between the area-wide large-scale integrating observations (WP-5) and the point-based irregular sparsely distributed in-situ measurements
- The development of a flexible, cloud-independent and cost-effective method for recording and mapping water quality parameters of surface waters
- To close the gap between direct in-situ measurements of substance inputs (AP-6) and substance discharge modeling from the catchments

The parameters which affect the electromagnetic reflectance spectra of water were the primary target variables in this subproject. In particular, these are total suspended solids (TSS), chlorophyll-a concentration (chl-a), as well as surface temperature (T) and turbidity or Secchi disk depth (SDD) of the water body. Furthermore, existing methods were used and adapted to determine parameters, which do not affect the reflectance spectrum of water such as phosphorus content (TP) and nitrogen content (N) by integrating data from other work packages.

WP 5 – Satellite based remote sensing

The quantitative estimation of the terrestrial material discharge potentials can be decisively improved by satellite-based recording of the catchment areas of the artificial lakes. The vegetation cover, dynamics and vitality of agricultural and forestry surfaces as well as different soil characteristics can be represented by satellite image data. Besides the vegetation, sealed areas, open ground and others are determined, so that direct conclusions can be drawn about the degree of total vegetation coverage. This information can then be used as a basis for the material discharge modeling.

The main objectives of WP 5 were:

- Further development of methods for the automated derivation of land cover to support substance discharge modeling from satellite-based images for water catchment areas.
- Determination of the influence of different land cover classes on the discharge of substances
- Ensuring the transferability of the developed methods to other vegetation zones, especially subtropics/tropics with test area in Brazil
- Modeling of the different vegetation cover rates (NDVI) over the vegetation period and derivation of the influence on the material discharge modeling

WP 6 – Water quality assessment

The aim of subproject WP 6 was to investigate the basic processes that determine the relationship between nutrient inputs and the resulting water quality in reservoirs in interaction with hydro-meteorological and operational boundary conditions. Furthermore, it was investigated how the relevant in-lake processes can be described on the basis of remote sensing data and which minimum requirements have to be met by accompanying in-situ measurements in the reservoir in order to be able to describe and predict the water quality and its dynamics with sufficient accuracy.

Specifically, the transport pathways for particle-bound and dissolved nutrients (N and P) in the reservoir were investigated with particular emphasis on vertical density stratification, density-driven currents, and vertical mixing of the water body using extensive field measurements. At the same time, modern optical methods for the collection of water quality data were used, further developed and optimized. These include immersion probes for reagent-free online determination of nutrients, algae groups, dissolved carbon compounds and organic pollutants.

The main objectives of WP 6 were:

- An improved process understanding of the role of in-lake transport processes for the fate of input nutrients and the interaction of nutrient inputs and meteorological boundary conditions in the development of algal and cyanobacterial blooms in density-stratified water bodies.
- Identify the role of density-driven currents on the vertical distribution of dissolved and particle-bound nutrients and the resulting biological availability.
- Based on the collected measurements and on process-oriented modeling, technical solutions were developed to describe the processes governing algal development and composition with a minimum effort of measurements and priority use of remote sensing data.

- For the in-situ sensors, the development of advanced algorithms for the use of the additional detection channels for the automatic correction of cross-sensitivities and subsurface correction.
- Optimization and adaptation of the wavelength sets currently in use.
- Implementation of the SOS data interface and the data transfer to connect the system to the central web-based infrastructure of the project.

WP 7 – Sensor Web- und Web Processing Architecture

The Wupperverband and 52°North worked in WP 7 on the development of a modular information system, with the help of which statements on water quality in dams and dam catchment areas can be derived from remote sensing data.

The focus of the conception is on the use of open standards for the web service interfaces and data models, as they have found their way into the INSPIRE guideline, for example. This ensures the transferability of the system to other dam catchment areas. This is an important prerequisite for the conception of long-term, integrated management strategies regarding water pollution control and the securing of the population's access to clean drinking water.

The main objectives of WP 7 were:

- the development of a data management component, which allows the use of spatio-temporally high-resolution satellite-based remote sensing data as well as hyperspectral measurement values and their linkage with in-situ measurement data.
- the integration of the specialized models from the sub-projects of the cooperation partners and the provision of the calculation results in the modular information system.
- the communication of the measurement data and results from the model calculations to the user by visualization in a web-based graphical user interface.

Within the framework of MuDak-WRM, the following technical work objectives were pursued.

- Development of a suitable, scalable data management component, which allows the management and access to the model calculation results, forecasts and remote sensing data available in the project.
- Integration of the specialized model programs from the subprojects of the cooperation partners
- Development of a visualization component, which allows access to the model calculation results, forecasts and remote sensing data available in the project.
- Use of open standards for the web service interfaces and data models.

5. Results

Overview:

The previously defined research questions were successfully addressed during the run of the MuDak project. The planed measurements and assessments were finished as planed with a successful data acquisition as a basis for the adaptation of the three models. During four individual large measurement campaigns at Passaúna and three measurement campaigns at the Große Dhünn reservoir pre-dam the actual ecological and operational state of the reservoirs was evaluated. Water quality sensors were successfully tested at the Große Dhünn reservoir and were later on permanently installed in the Passaúna reservoir. Time series of water quality data of more than one continuous year was achieved.

Sedimentation assessment revealed that the siltation process in the pre-dam of the great Dhünn reservoir is relatively slow due to limited erosion in the catchment. In contrast to this, the Passauna reservoir is affected by significant siltation and accumulation of nutrients, even though the actual status is mesotrophic.

Collected input data for the hydrological model and the emission model was processed and implemented. We coupled the results from the water balance model into the emission model, in order to improve the precision between the emissions from the different pathways. Final emission values were validated with the sediment field data.

The Sensor Web was further developed to visualize the real-time-transferred online data as well as various types of field data, like vertical profiles or processed satellite raster data.

Partners from all work packages participated in an extended training and transfer session during five days. In parallel to the monitoring activities, the applied methods and tools were explained to employees from the operating company in theory as well as in the field. Additionally, bi- and trilateral meetings took place to exchange work package-specific demands from the company and authorities.

Introduction of the Flyers as condensed project results:

In order to make the central results of the project better accessible, the project team created a set of “technical flyers” to condense the created knowledge. The flyers are intended to be less scientific and more useful for practical applications or implementation in the industry. The so prepared content may allow for a facilitated transfer from scientific results towards practical use. The flyers are located at the end of each work package.

5.1. Work package 1 – Substance input modeling and reservoir sedimentation status

5.1.1. Substance input modeling

5.1.1.1. Introduction and objectives

Passaúna catchment is characterized by a high anthropogenic activity, where around 35% of the catchment is covered by agricultural land and urban areas. The effects of this anthropogenic activity are expected to be visible also in the substance emissions of these areas into the water body. The focus of this work package was to initially assess the sediment and total Phosphorus (TP) emissions into the Passaúna River and the Great Dhünn reservoir (GDTS) and secondly to simplify the modeling approaches, for a facilitated transferability and applicability in other regions. For this purpose the Model of Regionalized Emissions (MoRE) was used and further developed (https://isww.iwg.kit.edu/MoRE.php).

The TP can follow different input pathways as shown in Figure 10. In the context of simplicity we focused on the most important pathways, which are explained in the below paragraphs. The most important pathways, especially for Passaúna where the emissions were expected higher, are the surface runoff and erosion due to the high rainfall intensities in the region and the input from the not connected households in the semi-formal and informal urban settlements in the catchment. While for GDTS the most important source of TP is the surface runoff.

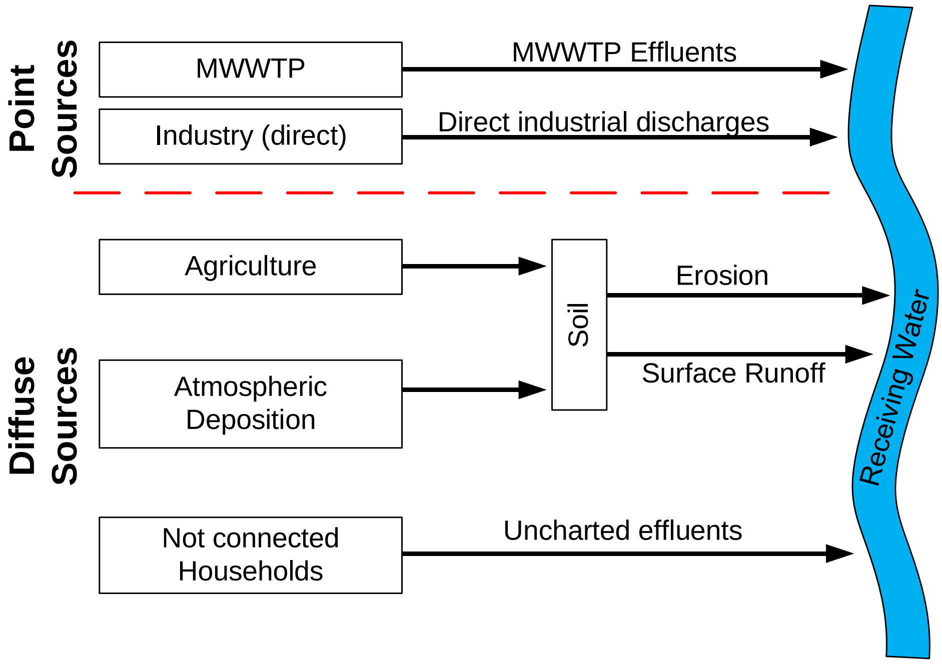


Figure 10: Reduced complexity of input pathways for the quantification of TP in the water bodies.

5.1.1.2. Preparation and method

P-input from surface runoff in Passaúna

Given the high rain intensity that may occur in the region, the P-input from the surface runoff from arable lands can play a significant role in the overall P-budget of the catchment. As there was no existing data about the dissolved P in surface runoff in the region, we conducted artificial rain experiments together with the researchers from the Department of Soil and Agricultural Engineering for quantifying the concentrations of dissolved P in the surface runoff (Figure 11). The sprinkling experiments were conducted in six locations in the Passaúna catchment. A these locations the sprinkling had a duration of up to 45 min while the rain intensity was set up to 120 mm/h at some locations. The water from the surface runoff was collected and brought to the laboratory and the concentration of orthophosphate was measured.

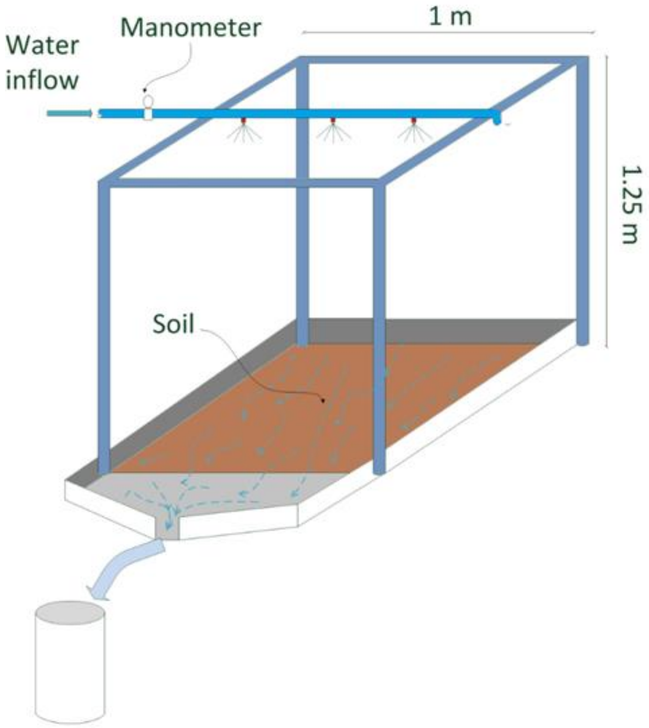


Figure 11: Schematic illustration of field rain experiments setup.

Near the areas where the sprinkling experiments were conducted, also soil samples were collected. These soil samples were brought to the laboratory, where a P-test was conducted. In this test, one gram of soil is mixed with 50 ml of water and shaken for 60 min (Figure 12, top). The mixture is afterwards passed through a 10-20 µm filter and finally the released orthophosphate concentration was measured. The final values of the released orthophosphate were set into relation with the values of the orthophosphate from the direct runoff during the sprinkling position and the regression curve of Figure 12, bottom was derived. As it can be seen there is a direct connection between the measured orthophosphate concentration from surface runoff and the orthophosphate concentration released from the P-test.

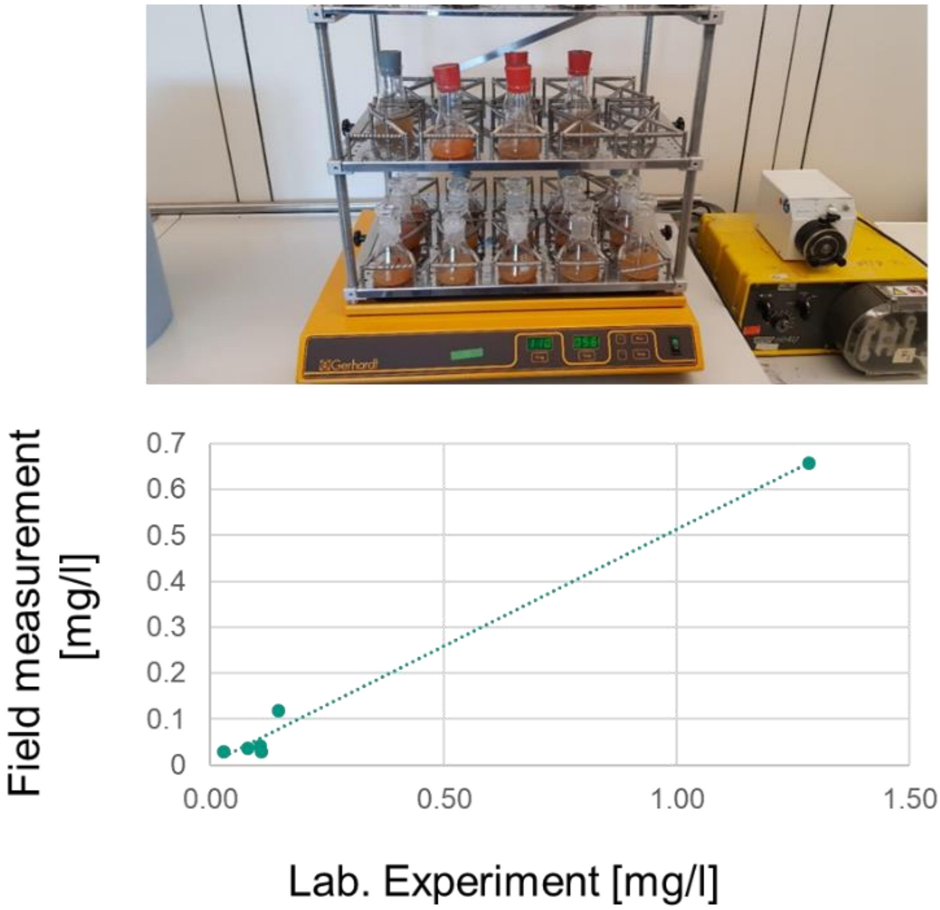


Figure 12: top: Dissolving experiments in the lab at IWG-SWW; bottom: Comparison between field measurements of dissolved Phosphorous and lab experiments.

As it was difficult to perform more sprinkling experiments, 24 soil samples were collected throughout the catchment (Figure 13) and to each of the samples the P-test was performed. Finally, the regression equation from Figure 12, bottom was implemented to the values of orthophosphate from the P-test, in order to derive the expected concentration of orthophosphate in the surface runoff. The values were interpolated via Inverse Distance Weighting (IDW) and a map of expected orthophosphate concentrations in the runoff was derived. By multiplication of these values with the surface runoff volumes delivered from the water balance model (WP2) the overall and specific orthophosphate mass from the catchment were calculated on a monthly basis. In MoRE the values of the specific load were averaged for a specific analytical unit (AU) and the overall load of P from the specific AU was calculated by multiplying the averaged specific load with the area of the AU.

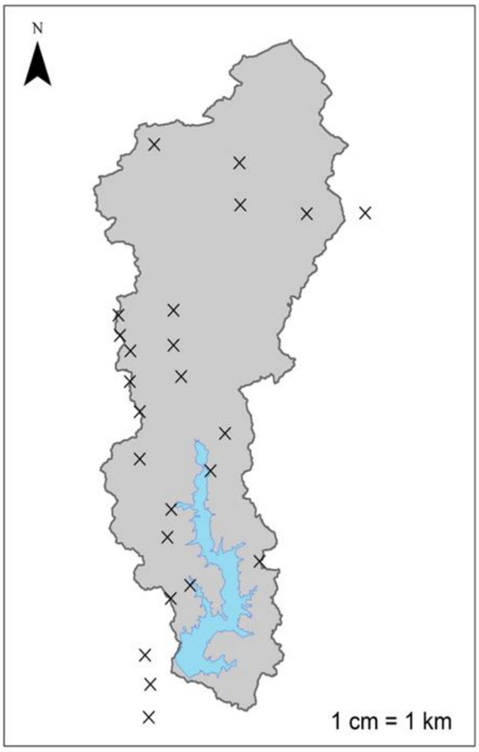


Figure 13: Location of the soil samples in and around the Passaúna catchment (grey area).

P from urban areas

The urban areas in the Passaúna catchment cover almost 10% of the overall catchment. In these urban areas, also semi-formal or even informal settlements are present. In such conditions the contribution of these areas in the overall P-budget of the catchment are expected to be significant. All the wastewater from the catchment is planned to be transported in the near catchment of Barigui River where also the wastewater treatment plant is located. However, as it can be seen from Figure 14, not all the urban areas are connected to the sewer system and even in areas with a sewer system there are direct emissions of wastewater into the river stretches. The calculation approach for the urban input was based on the number of inhabitants in each AU and the amount of TP emitted from an inhabitant per day (Figure 15). According to Sperling (2007) and Gomes de Quevedo and da Silva Paganini (2016), a person in Brazil emits in average 1g/day of TP. The data about the number of inhabitants were obtained from IBGE (https://www.ibge.gov.br/) based on the population census of 2010.

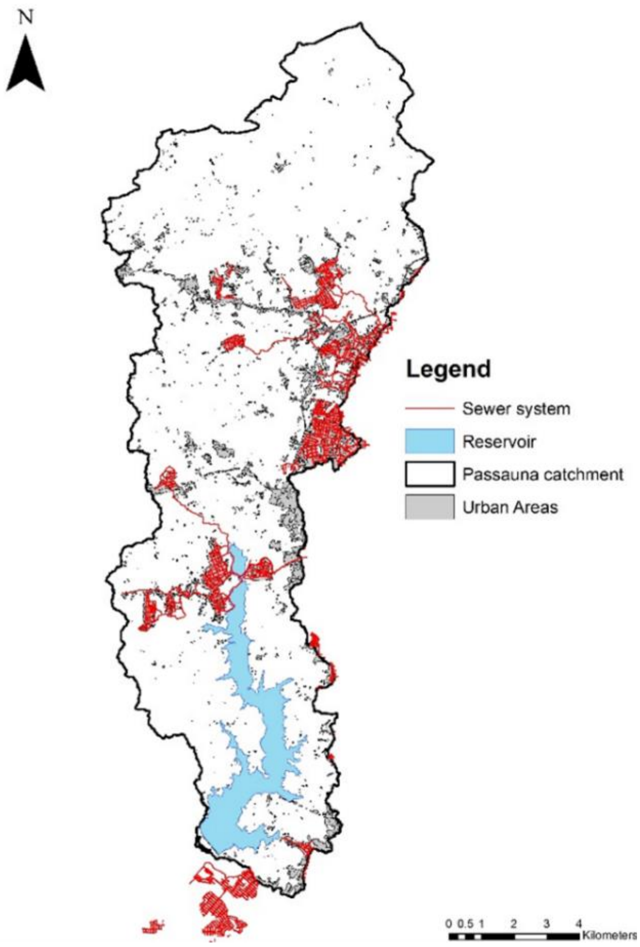


Figure 14: Urban areas and sewer system extension in the Passaúna river catchment. Ferraria settlement is located at the north-western end of the reservoir.

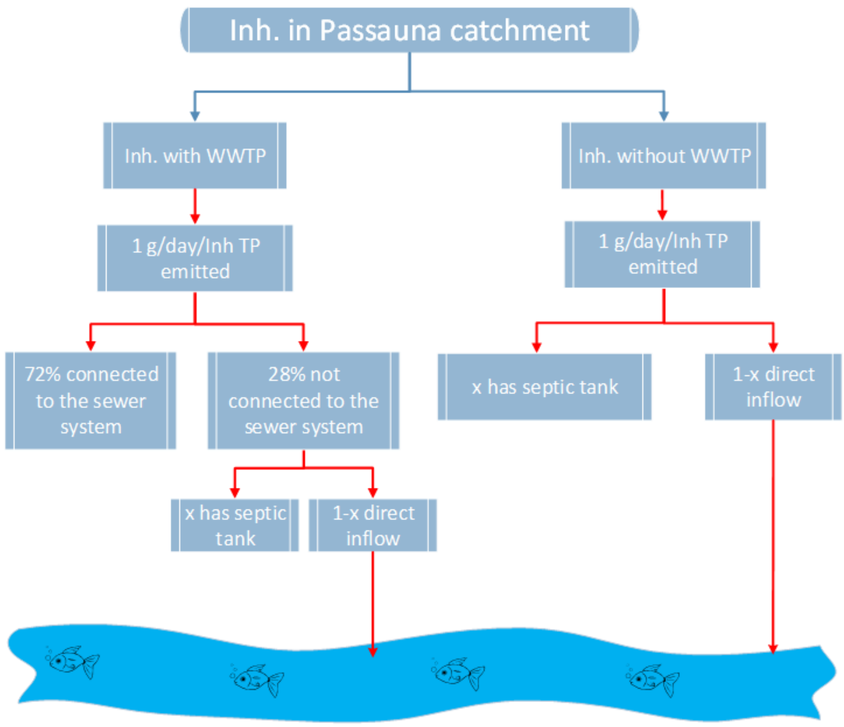


Figure 15: Calculation approach for the Phosphorous input from settlements.

The AUs were initially classified into areas with sewer system and areas without sewer system connection. The first step for the Passaúna catchment was to quantify how many inhabitants were connected to the sewer system in areas where a sewer system was present. For this purpose SANEPAR provided data for the area of Ferraria settlement regarding the status of connections to the sewer system. From the data analysis, it was concluded that from the households that had a water connection, only 72% had connection to the sewer system. From the data it was also observed that there was a uniform water consumption through the year therefore also the TP input through the year was assumed uniform, meaning that the TP export throughout the months of a year is equal. It was assumed that all other urban settlements in the catchment have similar characteristics regarding water consumption and connection to the sewage system. The second unknown in our approach was the share of inhabitants who do not have a sewer connection but have a decentralized system (e.g. septic tank). The calibration of the coeficient x (Figure 15), that represents the share of the inhabitants that use a decentralized system was achieved with the assistance of the Large Volume Sampler (LVS) data (Wagner 2019) and grab sampling campaigns in the Passaúna river, which measured the Phosphorous concentration over the time of the project.

Erosion

The high erodibility of soils in the region but also the high erosivity of the rain, suggest that a significant amount of soil is removed from the catchment. Together with the soil also the particulate Phosphorus is transported in the river stretches and afterwards in the reservoir. In order to calculate the TP input from soil loss, initially the soil loss and sediment yield into the water bodies had to be calculated. To calculate the sediment yield from the catchments we used an adapted form of Revised Universal Soil Loss Equation (RUSLE) (Alewell et al. 2019; Renard 1997; Wischmeier and Smith 1978), due to its simplicity and global applicability. In the present study, due to the adequate data availability, we modelled in a monthly time resolution. Mathematically RUSLE is presented in the following form:

$$\boldsymbol{A = L \cdot S \cdot R \cdot C \cdot K \cdot P} \quad \textbf{(1)}$$

A the soil loss at the investigated area
L the slope length factor
S the slope steepness factor
R the rainfall-runoff erosivity factor
C the cover management factor
K the soil erodibility factor
P the support practice factor

$$\boldsymbol{SI = A \cdot SDR} \quad \textbf{(2)}$$

SI the sediment input
SDR the sediment delivery ratio

For this study, the use of reduced complexity modeling approaches was aimed. An adapted RUSLE based model was used for calculating the sediment input from Passaúna catchment). A literature review was performed former to any modeling activities for defining the best possible approach for calculating each of the single coefficients. Each of the RUSLE factors represents one of the natural and anthropogenic phenomena as shown in (Figure 16). The integration of freely available satellite imagery in a high spatial and temporal resolution from the satellite platform Sentinel-2 and the existing precipitation data, made it possible to reduce the temporal resolution of the model to a monthly time step. For the calculation of the K-Factor, two soil sampling campaigns were conducted. From the collected soil samples, the soil properties were defined and subsequently the K-Factor was calculated based on a regional empirical relation Bouyoucos (1935). The empirical relation uses information about the texture of the soil and this information was derived from the 23 soil samples collected in the catchment (Figure 13). For the C-Factor, Normalized Difference Vegetation Index (NDVI) data from Sentinel-2 satellite platform was used. A locally derived empirical relation between the vegetation index and the C-Factor was applied (Waltrick et al. 2015). For the R-Factor assessment, this study relied on two different approaches, one on literature values of R-Factor and another one by using precipitation data recorded from the local authorities. In general, no land conservation practices were observed. Therefore, the P-Factor was set to maximum value of one.

To calculate finally the sediment input, the soil loss calculated from the RUSLE is multiplied with the SDR. The SDR calculation is based on the connectivity index approach of Vigiak et al. (2012), where coefficients integrating information about terrain and land cover are included in the equation. More details about the quantification approach followed for each factor can be found in Sotiri (2020).

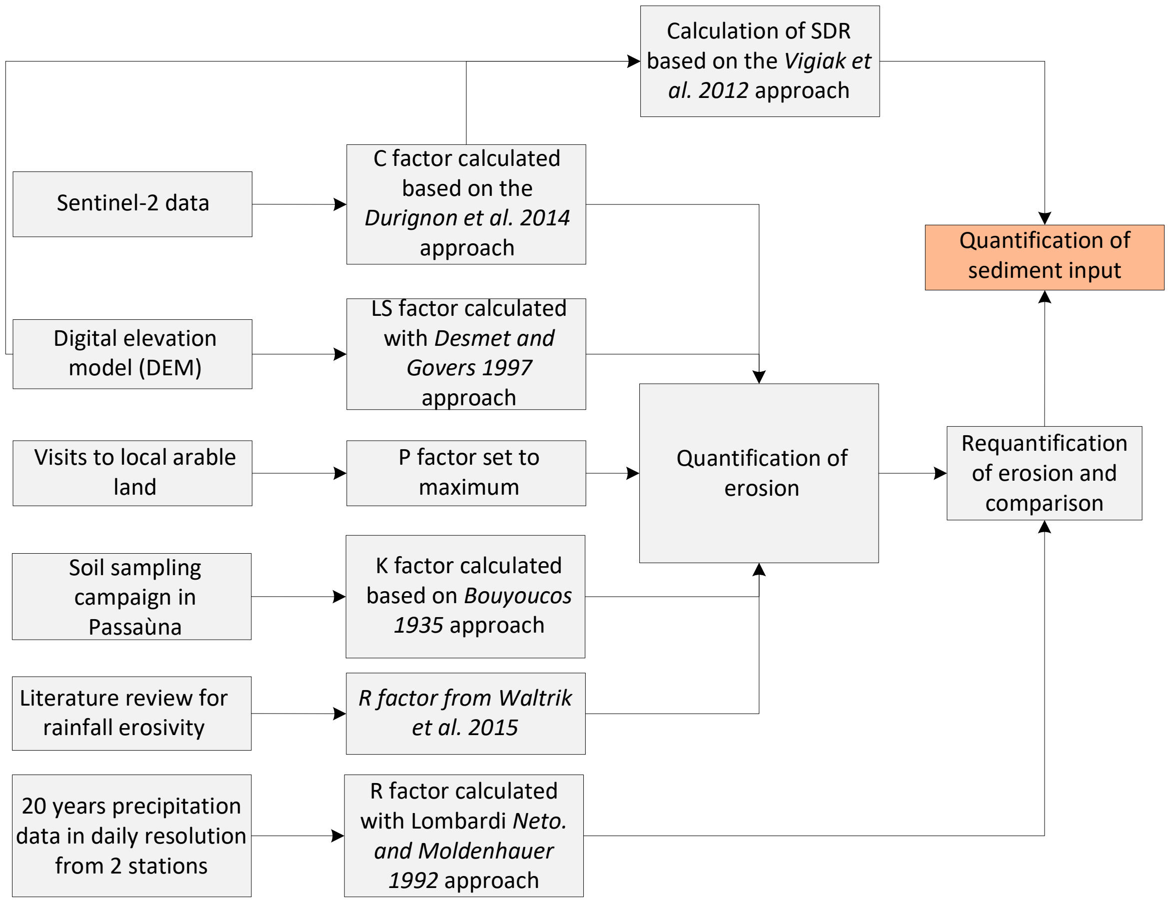


Figure 16: Work flow for the quantification of the sediment input.

The total Phosphorus input from the catchment was a product of the multiplication of sediment yield with the TP content from the top soil and with an enrichment ratio (ER) coefficient. The enrichment ratio coefficient is included in the equation as during the physical process of soil removal the fine fraction of soil is removed first. The TP is often bound to the fine fraction of the aggregate and therefore at the outlet of a catchment the TP in the sediment is higher than the TP content of the soil at the origin of the sediment. The TP content of the soil was derived from soil samples (Figure 13). The TP values were interpolated in order to have the TP content in the entire Passaúna catchment as done.

The enrichment ratio was calculated based on the empirical relation of Auerswald (1989) (Figure 17). Based on his findings, the enrichment ratio shows an exponential relation to the soil loss. As the soil loss for the Passauna catchment was calculated in a monthly time step also the enrichment ratio was calculated in a monthly timestep.

$$ER = 2.53 \cdot A^{-0.21}$$

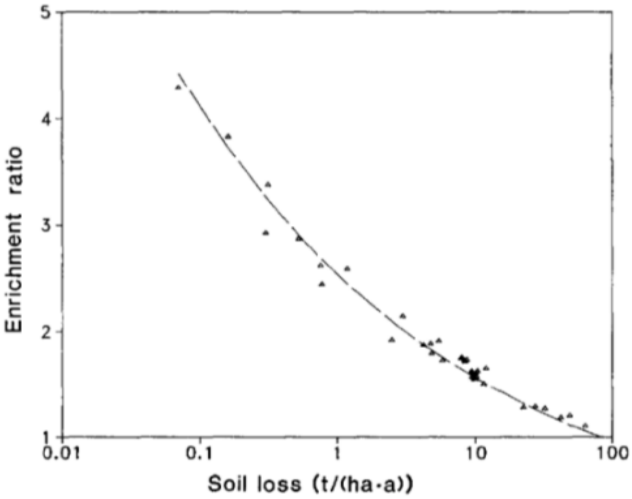


Figure 17: Derivation of the enrichment ratio after Auerswald (1989)

5.1.1.3. Results

TP Surface runoff

As it can be seen from the below figure the highest orthophosphate specific load is incoming from the western and northwestern part of the catchment. However, the entire area of the catchment is showing relatively low specific loads. Despite the average and high values of TP content observed in the soil, the Phosphorus is not being easily dissolved when it is present in the surface runoff. From a further investigation it was observed that the excess of Iron (Fe) in the soil does not allow the Phosphorus to be released in the water. The existence of high Fe content in the topsoil confined the overall amount of the TP reached the water body to only 320 kg a^{-1}.

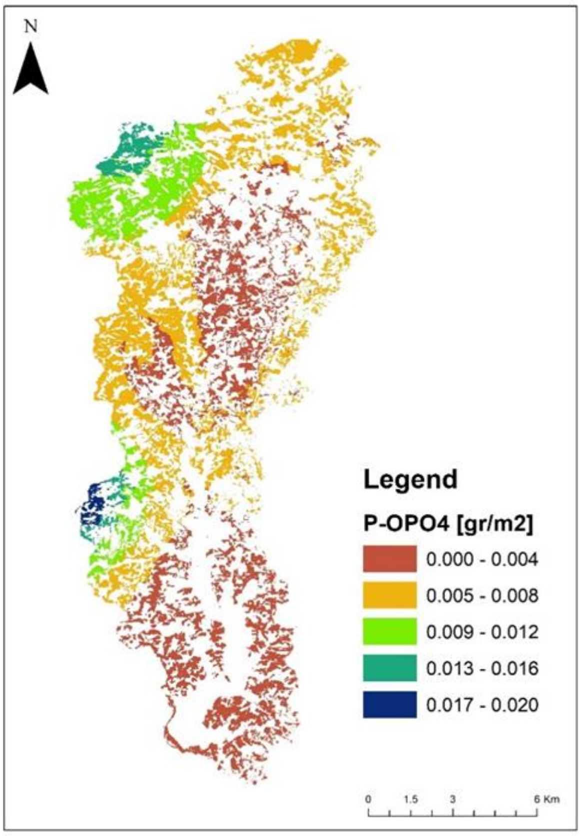


Figure 18: Top soil content of P-OPO_4 in the Passaúna catchment.

The quantification of P-Input from surface runoff in the Große Dhünntalsperre followed an easier process. For the catchment, data of P_2O_5 content in topsoil were available from "Fachinformationssystem Stoffliche Bodenbelastung (StoBo) www.stobo.nrw.de" for pasture and arable land. These values were transformed in orthophosphate concentration by the relation discovered by the IWG-SWW for Baden Württemberg (unpublished data). The procedure followed to transform the concentrations into masses, was similar for the Passaúna case; by multiplying with the surface runoff delivered from WP2. As it can be seen from Figure 19, most of the P (2.2 tons) in the reservoir originates from pastureland. The low input flux from agricultural land can be attributed to the low coverage of the agricultural land in the GDTS catchment, while the relatively high input from pastureland and forests, is simply linked to the high coverage of forest and pastureland (combined they cover more than 90% of the catchment area).

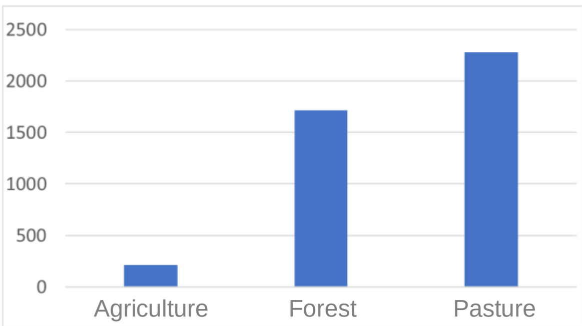


Figure 19: Phosphorous flux from the catchment to Große Dhünntalsperre in tons, divided over the relevant pathways.

Urban Input

The LVS measured 19 baseflow events from March 2018 until March 2019 and an overall measuring duration of 165 days. As in the samling no flood events were included, the load measured from the baseflow represents only the input from industrial areas and not connected housholds. As Passsauna is classified as Environmentaly Protected Area it was assumed that the industry discharges were zero as the general trend shows most of the industry located in the Barigui catchment. The overall load in the river was atrributed to the direct dischrges of wastewater into the river from the unconected housholds. The finding from the overall measuring time were extrapolated to the entire year and from the baseflow of Passauna river a total of 3.7 tons of TP were measured. The application of this value in the scheme of Figure 15 implies that only 7% of the not connected housholds have a decentralized systems and 93% of the TP is introduced as direct untreated sewage. Due to the relatively accurate data for the baseflow load, the top down approach was used for having an accurate calculation methodology. Based on data regarding the connection of the inhabitanst to the sewer system, now a calibrated model can be used for the quantification of the TP from urban areas also for future scenarios.

TP input from Erosion

The temporal distribution of TP incoming as particulate matter, follows the same pattern as the sediment input, indicating that the months of early spring September and October are the most relevant months (Figure 21). These two months compose 27% (20% of the yearly input in October) of the yearly TP input from Passaúna catchment. The yearly TP input in particulate form, due to soil loss, is 67.2 tons annually. When comparing the different sources of Phosphorus input into the Passaúna river, it can be seen that soil loss/erosion is the most important contributor (Figure 22). TP input, due to soil loss, composes 93% of the total TP input.

The most important source of sediment input as it can be seen from Figure 20 is cropland with 55% followed afterwards by scrubland and pastureland with respectively 16 and 12%. Due to the high rainfall erosivity and low land coverage in the early months of spring, September and October are the months with the higher sediment input with respectively 7,500 and 6,000 tons of sediment (Figure 21). In overall it was calculated that a average of 54,800 ton/a of sediment is reaching Passaúna reservoir during the 20 years that the precipitation data was available.

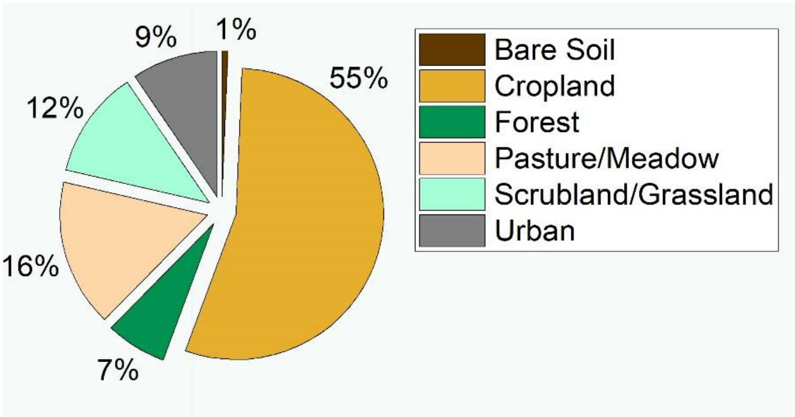


Figure 20: Overview of sediment input shares by land use class in the Passaúna catchment.

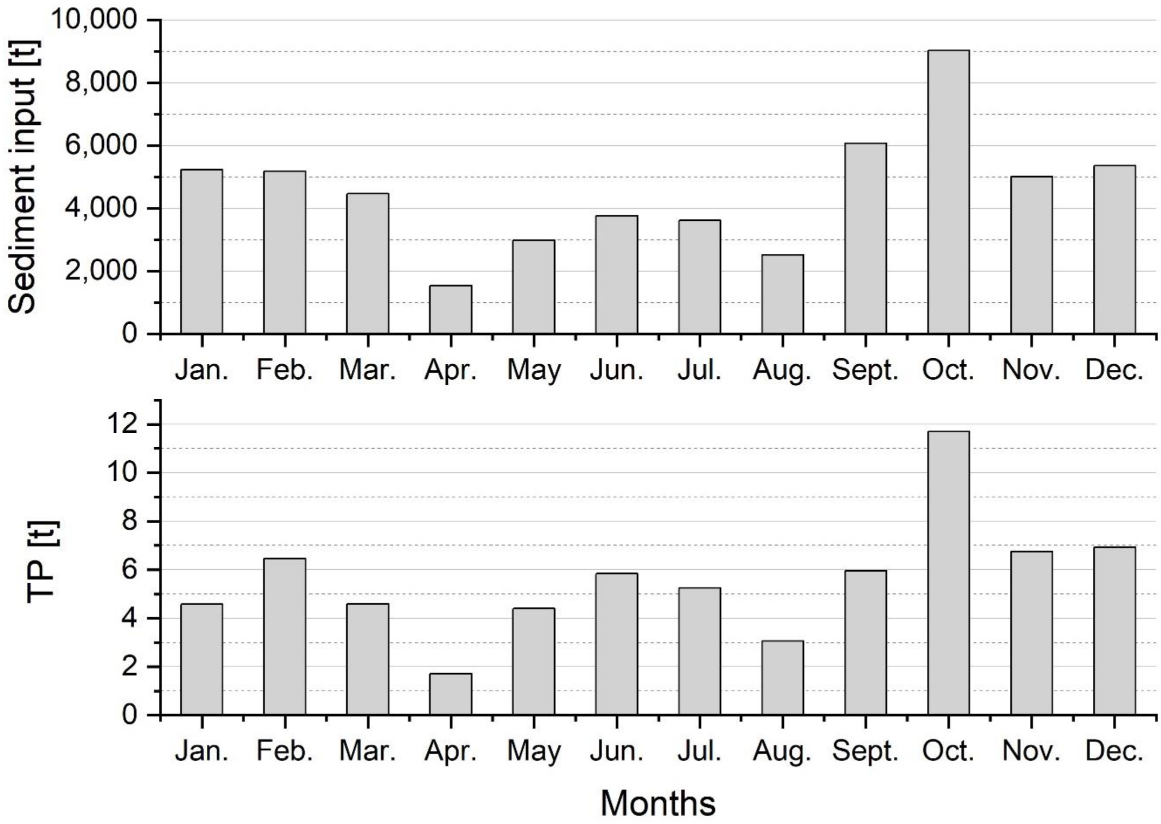


Figure 21: Sediment input from Passaúna catchment, resolved over the months of a year.

Finally, as it can be observed in Figure 22, the temporal distribution of TP incoming from particulate matter follows the same pattern as the sediment input indicating that the months of early spring (September and October) are the most relevant months. These two months compose 27% (20% of the yearly input in October) of the yearly TP input from Passaúna catchment. The yearly TP input in particulate form due to soil loss is 67.2 tons annually. When comparing the different sources of Phosphorus input in the Passaúna River, it can be seen (figure x) soil loss/erosion is the most important contributor. TP input due to soil loss compose 93% of the total TP input.

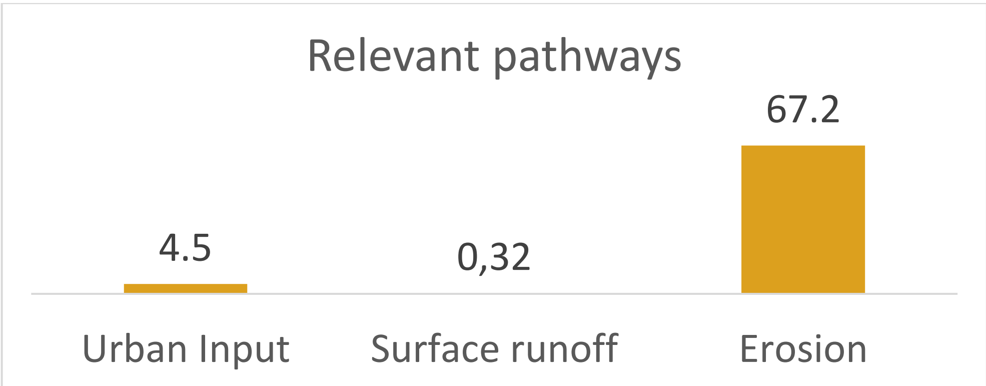
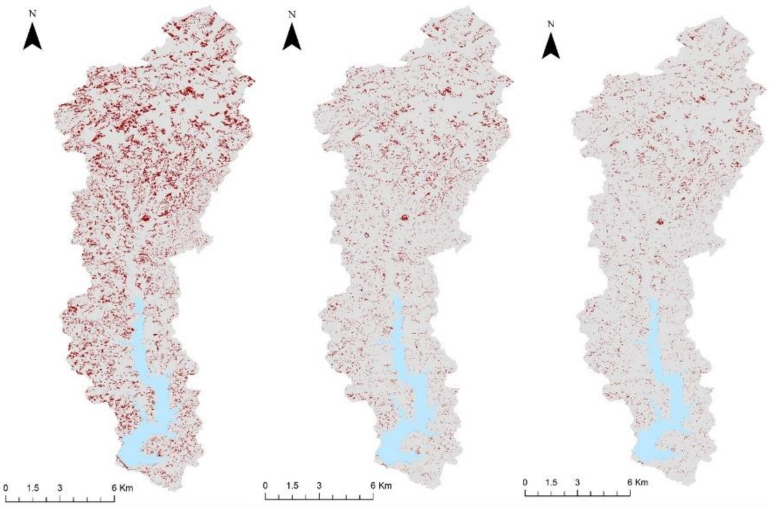


Figure 22: Comparison of absolute P-emissions (t/a) from three different pathways.

The input data availability in high temporal and spatial resolution enabled an increased temporal and spatial precision of the model output. The next step was to assess how this kind of data could be used for a better management of the catchment. As erosion was the main contributor in terms of TP input, first an analysis was performed, on how the soil loss and sediment input from the catchment could be reduced by afforestation in the most problematic areas, characterized by high soil loss rates. For this purpose, three scenarios were investigated; more specifically afforestation of areas with more than 100 (scenario A), 200 (scenario B) and 250 tons ha^{-1} a^{-1} (scenario C), which account respectively for 12%, 5%, and 3% of the catchment area (Figure 23). From our calculations it was found, that with full afforestation of these areas a reduction of 50%, 27%, and 26% of the annual sediment input could be achieved. Such a measure, apart from tackling the soil degradation in the catchment, can also significantly contribute to increase the reservoir lifetime and hinder water quality deterioration.



	A	B	C
	>100 (ton ha^{-1} a^{-1})	>200 (ton ha^{-1} a^{-1})	>250 (ton ha^{-1} a^{-1}
Area (ha)	1757 (12%)	720.3 (5%)	510 (3%)
Sed. Input Reduction (%)	50%	27%	26%

Figure 23: Areal coverage of problematic areas for scenario A, B and C and the respective reduction of sediment input from afforestation.

October and September are the most important months in regard to sediment input and soil loss and TP input. Especially during October the combination of the RUSLE factors is the most effective in terms of sediment production/erosion and TP mobilization. Figure 24 shows the combination of C- and R-factors for the three most characteristic months of the year. In case of the C-factor, October has the same values as July, which is one of the driest and coldest months of the year and has the lowest vegetation cover. As far as the R-factor is concerned, the erosivity is as high as the erosivity in the month of January, which is the month with the highest rainfall (together with October and February). For October, the worst combination is present as the rainfall erosivity is maximal, while the vegetation cover is minimal. This combination of factors produces the highest soil loss within the catchment. If proper land management strategies, like crop rotation, application of crop residues and cover crops over unprotected soil during winter and spring months (April-October) are applied, a significant reduction of the sediment input and TP input could be achieved (Sullivan 2003b, 2003a; SoCo Project Team 2009).

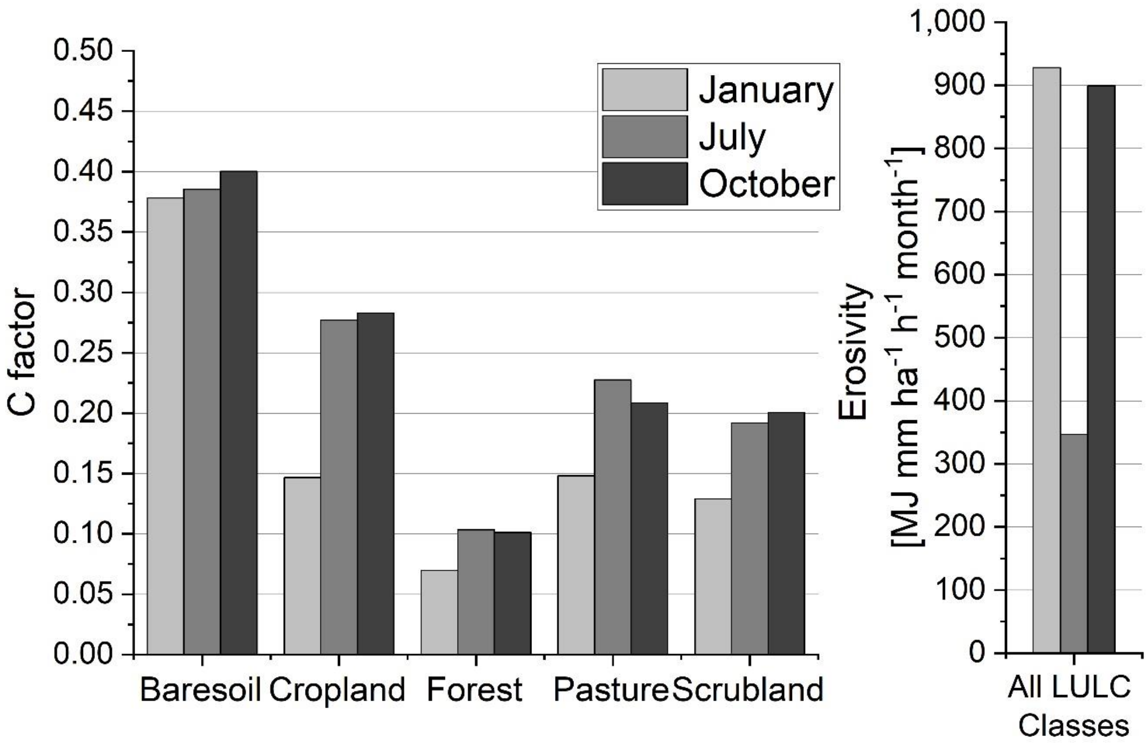


Figure 24: C-factor and R-factor for three months (January, July, October).

The application of RUSLE-based models, in monthly resolution as decision support system, due to the increased performance of the model in both, spatial and temporal dimension, can lead to an improved river basin management. The free availability of the data makes the implementation of such approaches also globally applicable. Specifically, as shown in the previous paragraphs, the inclusion of NDVI data can enable the planning of management activities in high spatial resolution, but also aiming in the temporal dimension by highlighting the most problematic months of the year. The latter is of high importance as it may lead to reduced catchment management costs.

5.1.2. Reservoir sedimentation status

Accumulated solids play a crucial role for the lifetime of a reservoir. First, as they are the main factor, which reduces reservoir's storage capacity by accumulating in the lakebed, and secondly as they are an important factor accelerating water quality deterioration. The figures about global reservoir sedimentation illustrate a difficult situation. It is estimated, that the annual storage loss due to sedimentation reaches 0.5-1% of the overall storage volume (Schleiss et al. 2016). Sumi (2004) calculated an average storage loss rate of 0.52% yearly. Basson (2009) states that in Asia 70% of the volume used for irrigation will be lost by 2025, while the volume used for hydropower will be reduced to 20% by 2035 (Schleiss et al. 2016). Vörösmarty et al. (2003) estimated that more than 53% of the global sediment flux in regulated basins is trapped in reservoirs. While finally, Annandale (2014) claims that the world net storage capacity has been declining since 1995, as the construction of new storage capacity is lower than the loss of the existing storage capacity from sedimentation.

5.1.2.1. Introduction and objectives

For the management of the reservoir in terms of quantity as well as water quality aspects, it is essential to know the siltation rate and also the sediment distribution inside the reservoir. For many reservoirs this information is not available or only available in an insufficient resolution. Sediment thickness distribution can contribute to answer fundamental scientific questions concerning the deposition, resuspension, and transport dynamics in a reservoir.

The majority of the current guidelines suggest that the most accurate way for computing the sedimentation rate of an existing reservoir is topographic differencing through subsequent bathymetric surveys (Bruk 1985; Carvalho et al. 2000; U.S. Department of the Interior, Bureau of Reclamation 2006; Morris and Fan 2010; Annandale et al. 2016; Central Water Commission and Central Dam Safety Organisation 2019). The application of such an approach has certain constraints, especially in the oldest reservoirs where the existing topographical information is in insufficient accuracy or it does not exist. For this case, we investigated the possibility of applying alternative approaches for assessing the sediment volume in the Passaúna reservoir independent from the existing topographic data (Figure 25). The two major objectives of the section were initially to use a combined approach of remote sensing and conventional sampling methods for accurate measurements of the sediment thickness in the Passaúna reservoir, and secondly to assess the general applicability of the methods for different types of reservoirs based on the sediment characteristics. An accurate sediment distribution pattern is of double importance, as apart from supporting a sustainable management of the reservoir, it can also contribute in answering fundamental scientific questions concerning the deposition, resuspension, and transport dynamics in a reservoir. The findings of the sections were also discussed in the scientific contribution of Sotiri et al. 2021, which is in press.

The main task of this sub-work package was to generate precise validation data for the catchment erosion modeling. The data should include yearly accumulation rates of sediment mass, but also should give a good number of the amount of accumulated phosphorous inside the reservoir. The distribution of various sediment types (e.g. grain size) was additionally used as input parameters in WP3.

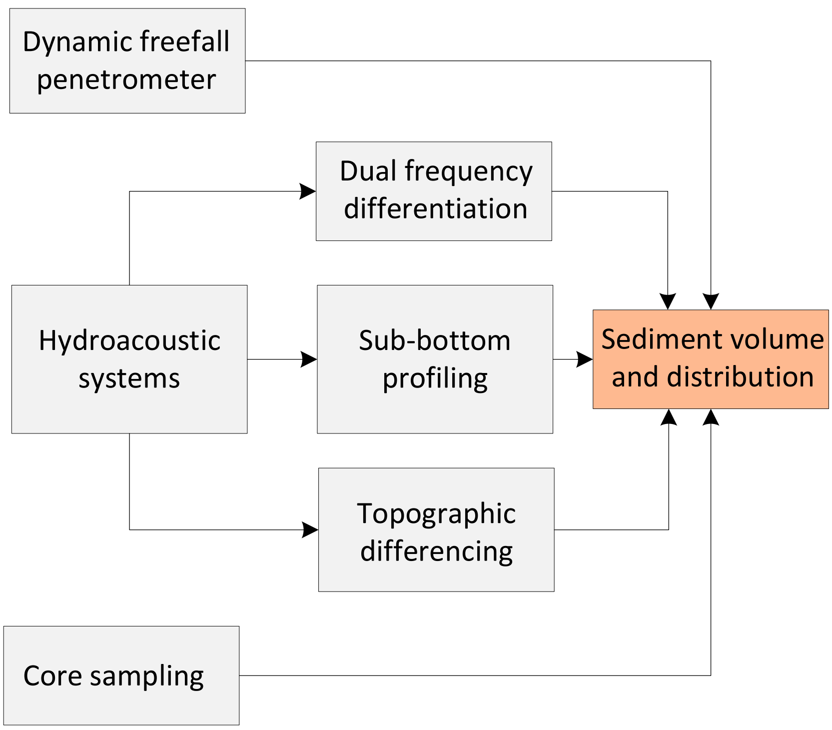


Figure 25: Schematic overview of the applied techniques for sediment detection.

5.1.2.2. Methods and Preparation

Sediment sampling

Sediment core sampling is a method that can help for the documentation of the sediment thickness, when the cores are undisturbed and the sampling device penetrates to the pre-impoundment soil. For this study, a “Niederreiter 90” corer manufactured by Uwitec was used. The corer consists of a metallic stainless-steel structure and replaceable 86 mm diameter PVC tube. If operated only by gravity, the corer has a weight of 8 kg. In order to have a deeper sediment penetration, we incorporated an additional 7 kg weight, which can be operated also as a hammer to penetrate harder sediments. The corer is easy to transport. It is connected to a portable manual winch, which can be installed in any type of survey vessel and operates at water depths of up to 100 m. Due to logistic limitations, liners up to 100 cm length were used (Sotiri 2021 in press).

In total 23 sediment cores and also seven sediment grab samples were taken in the Passaúna reservoir. After sampling, the sediment layers and their lengths were noted. Additionally, physical parameters of the sediment, like wet bulk density and granulometry, were determined in the laboratory for the differentiation between sediment and pre-impoundment soil, but also to characterize the sediment material. The information from core samples was mainly used to compare the actual sediment thickness with the penetrometer and hydroacoustic data and not for the overall volumetric assessment or spatial distribution of the sediment.

Topographic differencing

The high-resolution bathymetric survey was conducted using a WASSP F3Xi multibeam echo sounder. The system has a frequency of 160 kHz frequency, emits simultaneously 224 single beams and has an opening angle of 120°, which results in a swath width of ca. three times the water depth. The multibeam was connected with a Hemisphere V123 Compass for location and heading information and with a WSP-038 IMU unit for Roll/Pitch (0.25° accuracy) and heave (5 cm accuracy) correction. The system allowed for a vertical resolution of ±2 cm and an average horizontal resolution of ~20 cm. Since the outer beams of each multibeam system tend to produce more errors than the inner beams, large parts of the survey were conducted with 50% beam overlap. The survey duration was ~50 hours (ca. 300 km of boat tracks) and created 1000 GB of data.

As there was no previous bathymetric map and the existing topographic map was of insufficient accuracy, the recorded bathymetric data was used to create an actual storage-elevation curve. The actual storage-elevation curve was compared with the historic storage-elevation curve, which was being used until recently, by the reservoir operator Sanepar, in order to define whether significant storage loss had been taking place in the reservoir.

Linear single-beam hydroacoustic system EA400

The second acoustic system, that we used was the EA400 (Kongsberg Inc. 2006). The EA400 is a single-beam dual-frequency linear echosounder, which emits two primary frequencies of 200 and 38 kHz. The EA400 survey aimed an the investigation of the difference between the actual sediment water interface (SWI) from the 200 kHz soundwave and the depth of the strongest sub-bottom reflectance layer, obtained by the 38 kHz soundwave. The transducer was installed on an aluminum vessel with an incidence angle of 0° and the submersion depth was set to 45 cm. The measured profiles included (stable) static and (moving) dynamic profiles. During the static profiles, the boat was stabilized with three anchors and the water column and sediment was ensonified for a minimum period of 40 seconds (ca. 400 pings). The static profiles were recorded at each ground truthing position before the sediment sampling procedure, to obtain an undisturbed acoustic response from the sediment layers. During driving, the EA 400 was set to an input power of 100 W, a pulse length of 0.256 ms for the 200 kHz frequency and 0.512 ms for the 38 kHz frequency (Sotiri 2020).

Initially, the recorded data was imported in the Sonar5Pro software (Balk and Lindem 2014) where the recorded data was split in two channels and afterwards visualized. The bottom line (SWI), which was captured by the 200 kHz (Z200) was detected automatically via the automatic bottom detection function of the software, while the penetration depth line of the 38 kHz (Z38) was drawn manually for each line as shown in (Figure 26). Afterwards, the coordinates and the depth of each measured point were exported in ASCII format and imported in ArcMap. Finally, an interpolation using the Inverse Distance Weighting (IDW) technique was performed, and the final sediment distribution in the reservoir was visualized. Regarding the accuracy of the method, in the deepest areas (~18m), the 200 kHz pulse integrates information from a footprint area of up to 0.8 m^2, while the 38 kHz pulses integrate information from a footprint area of up to 7 m^2. In vertical direction, the accuracy of the measurement relies on the pulse length. With the above mentioned pulse lengths, the 200 kHz achieved a vertical echogram resolution of 2.4 cm while the 38 kHz pulse length achieved an echogram resolution of 9.6 cm, which is also the maximum accuracy of the method (Sotiri et al. 2021).

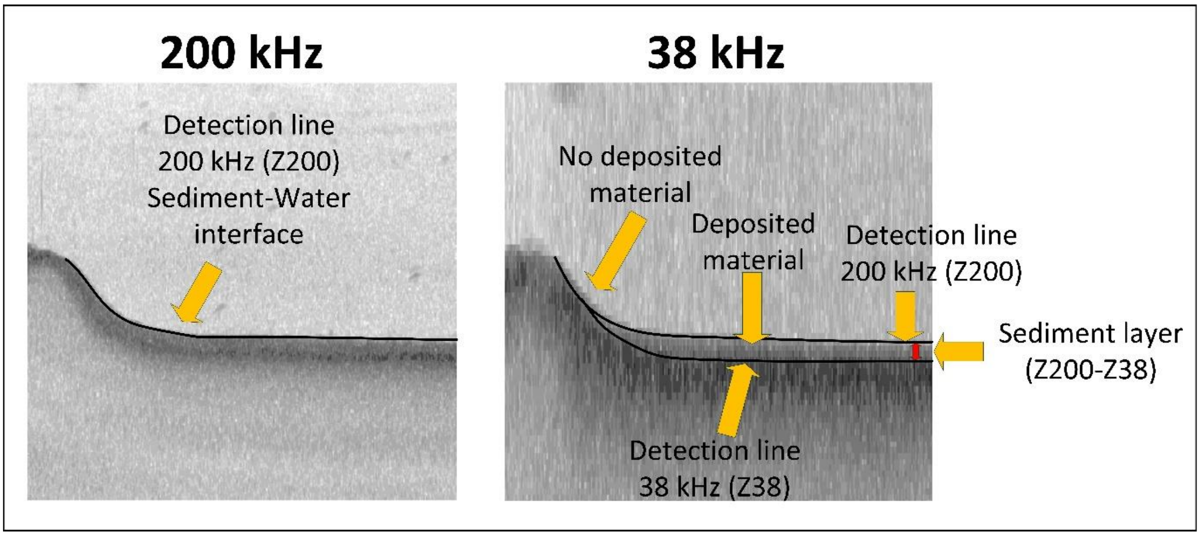


Figure 26: Calculation of sediment thickness based on the dual-frequency approach. The sediment thickness was calculated by subtracting the actual sediment-water interface depth (Z200) from the pre-impoundment bottom detected from the 38 kHz (Z38).

Parametric hydro-acoustic system

The third acoustic system used in this study was the SES2000 Compact produced by Innomar Technologies GmbH. The SES2000 Compact is a parametric multi-frequency single-beam echosounder, which can cover water depth ranges from 0.5–400 m. Depending on the sediment type and noise, it penetrates the sediment up to 40 m. Its layer resolution varies from 1–5 cm. It has a primary frequency band of 85–115 kHz for acquisition of the bottom track and a secondary low frequency band of 4–15 kHz for the sub-bottom data. The sub-bottom profilers have the advantage of high penetration combined with high resolution because of the low frequency waves that arise due to the nonlinear propagation of the sound wave. Such systems can be an effective monitoring solution in reservoirs like Passaúna, where there is a low sedimentation rate (in the range of some cm a-1) (Missiaen et al. 2008; Yutsis et al. 2014). For this case, waves with 4, 6, 10, 12, 15 kHz frequencies were used.

The acoustic system was connected to a Leica 1200 DGPS system to reach a positioning precision in the cm range. CTD profiles (CastAway®-CTD) were recorder for sound speed corrections. As with the linear echosounder, also here the measured profiles included (stable) static and (moving) dynamic profiles following. In order to have an optimal spatial coverage of the reservoir, the measurements' cross section of the reservoir were recorded at an interval of 50–100 m. In addition also a limited number of longitudinal transects were recorded. Further detailed description of the SES2000 survey are given in (Sotiri et al. 2019).

The recorded data was visualized and processed in ISE2 software (Innomar Technologies GmbH 2016). The sediment layer were drawn manually while for the water sediment interface (SWI), the automatic bottom detection algorithm of the software was applied. Occasionally the bottom detection line was manually corrected in the cases when errors were present. The sediment thickness was derived by subtracting from the depth of the present water sediment interface, the depth of the former lake bottom as shown in Figure 27.

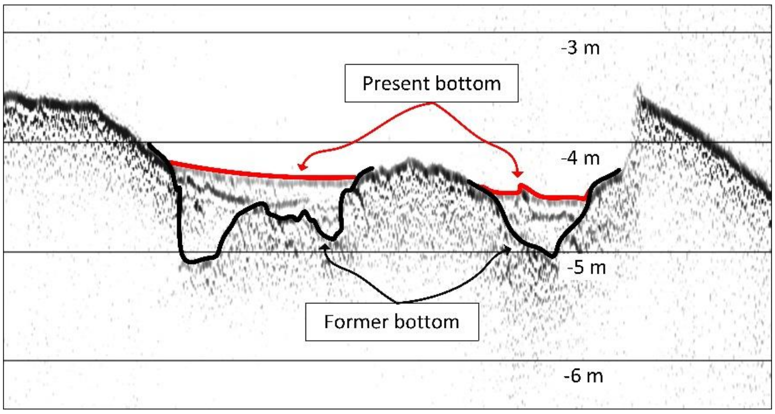


Figure 27: Transect from a 12 kHz line with the SESS2000 Compact, highlighting the pre-impoundment bottom (black line) and the actual sediment water interface (red line).

GraviProbe

The final system used to assess the spatial thickness distribution of the unconsolidated sediment layer, was the portable dynamic free-fall penetrometer (DFFP) GraviProbe. The GraviProbe (GP) is made of stainless steel, has a weight of 8 kg, has a length of 960 mm, and a diameter of 50 mm (Figure 29). The GP is released vertically from the boat. Because of its optimized shape it accelerates and penetrated the lake bottom depending also on the bottom type. Internally it contains accelerometers, pressure sensors, and data loggers that can record up to 5120 pressure and acceleration measurements per second and can achieve a precision of ± 1 (Seifert and Kopf 2012). The recorded data are used as input data for dynamic model that determines the geotechnical parameters dynamic cone penetration resistance (DCPR) and undrained shear strength (USS). The probe communicates via WiFi with an Android device (tablet or mobile phone) from which the data can be downloaded after each deployment and referenced spatially. The GraviProbe has been used for the characterization of the top layer of the sediment in marine, harbor and freshwater while there is no application for the detection of sediment magnitude (Stark et al. 2009; Stark et al. 2012; Albatal and Stark 2017; Kirichek and Rutgers 2019; Kirichek et al. 2020). The sediment layers from a DCPR curve can be detected either by the spikes that a curve presents or by an abrupt change in the DCPR curve (Figure 28).

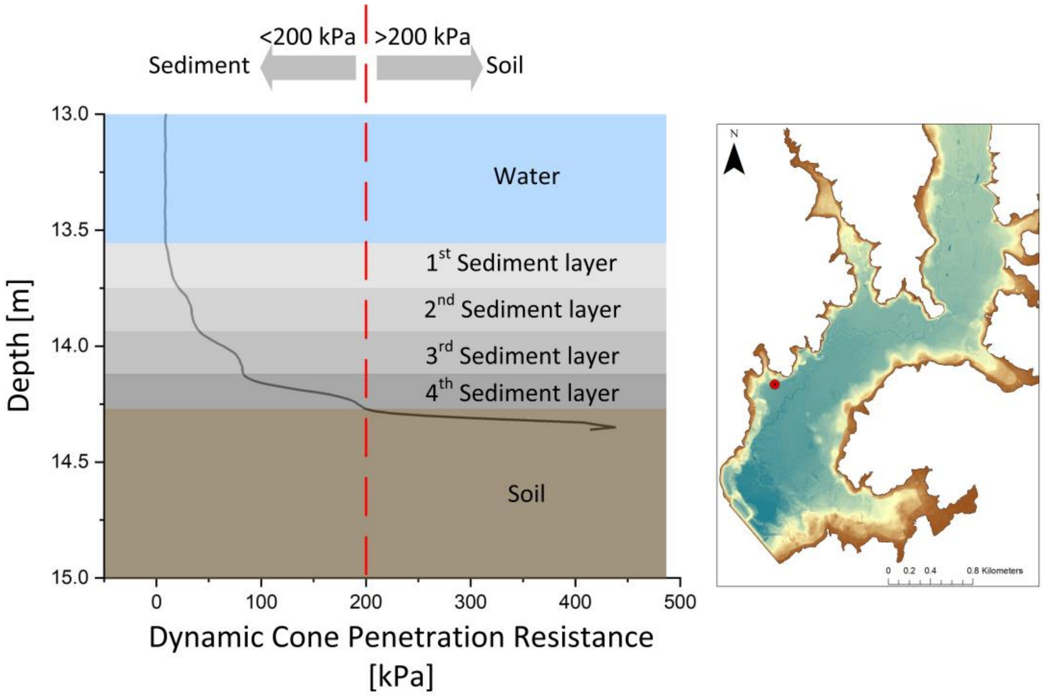


Figure 28: GP profile that shows the layering effect in the sediment.

A total of 134 GP measurements were conducted, covering all the important parts of the reservoir (sidearms, inlet, thalweg, dam area and intake area). For a better investigation of the lateral distribution of the sediment, also six cross section profiles were measured in higher detail. The measurements were finally interpolated using the IDW technique in ArcGIS 10.5 and the overall sediment distribution in the reservoir was presented in a raster map.

Figure 29: Photo of the GP before (left) and after deployment (right).

5.1.2.3. Results

Sediment sampling

In total, 23 core samples were collected with a length ranging from 12 cm (C2) in an area with high water velocity to 92 cm (C14) (Figure 30). C14 is located in a sidearm, which collects the water from a drainage basin with high agricultural activity, and is therefore characterized from high soil loss and sediment yield. Most of the accumulation is observed in the thalweg as it can be deducted from the length of the cores (C1, C3, C7, C10, C11, C18, and C21) located in the central part of the reservoir.

The cores showed that the lake bottom is covered by unconsolidated fine-grained low-density material. The Wet Bulk Density (WBD) values ranged between 0.7 g/cm^3 in the deep areas (>8 m) due to gas voids in the sediment to 1.6 g/cm^3 in the shallow areas with an average WBD of 1.12 g/cm^3. Including also the information from seven grab samples, 19 out of 30 samples consisted of more than 95% of silt-clay material (<63 µm) (Sotiri et al. 2019). The samples are also characterized by a high organic share with an average LOI of 17%, with maximum values measured in C18 (50.9%) and the lowest from a grab sample located in an area with high water velocities at distance of five meters north from C2 (8.4%) (Sotiri 2020).

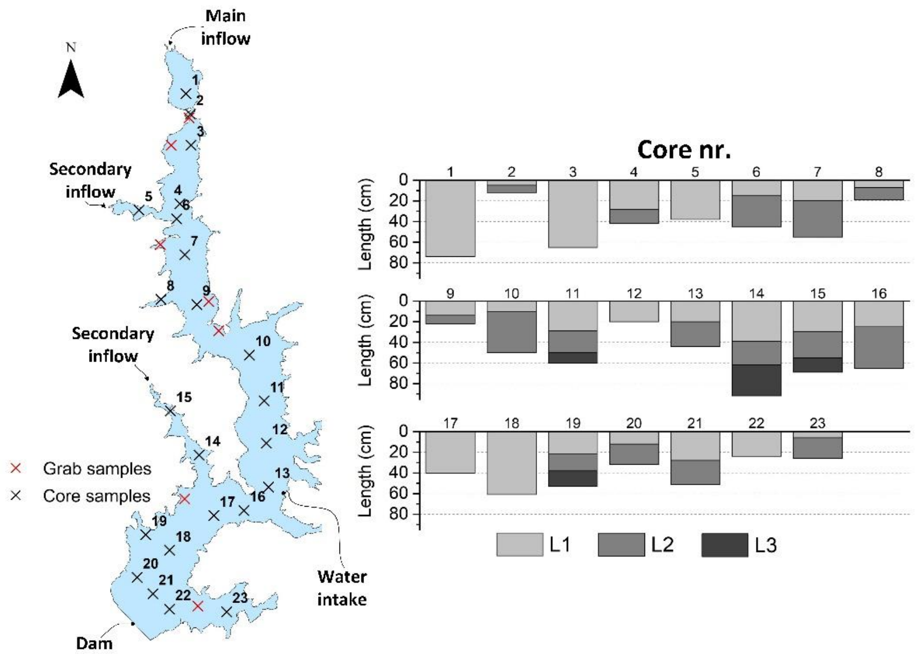


Figure 30: Location and length of core samples in the Passaúna reservoir. L1, L2 and L3 refer to the layers encountered in the samples where L1 is the layer near the SWI while L3 refers to the deeper sediment layers. Core numbers are listed based on their location from north to south.

Multibeam hydro-acoustic system - WASSP F3Xi

From the bathymetric survey, a map with a 20 cm raster resolution was created. The bathymetric map was the base for the new elevation-storage curve (ESC) of the reservoir (Figure 31). The reservoir has a total storage of 69.3 hm^3 at normal operational level (887.2 masl). The dead storage is 19.5 hm^3, or 28% of the overall volume of the reservoir. The maximum water depth of 18.1 m was recorded near the bottom outlet at 869.1 masl.

The comparison of the actual ESC with the former ESC, shows that the actual volume at some depths is larger than at the time of impoundment. Such a fact can be attributed either to erosion at the reservoir bottom or to the inaccuracies of the old ESC. As the velocities in the reservoir are minimal and cannot significantly erode the pre-impoundment lakebed, it seems that the cause for such a difference between the curves exists, because of the low accuracy of the historic ESC.

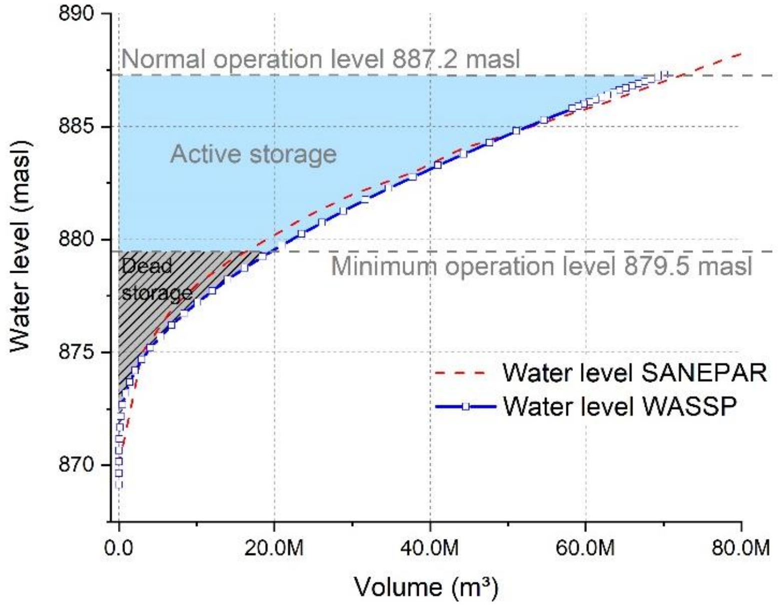


Figure 31: Comparison between elevation-storage curve derived from the WASSP multibeam system, and the existing curve.

Linear single-beam hydroacoustic system EA400

From the dual frequency approach, it was found, that the reservoir has an average sediment thickness of 36 cm. Most of the sediment, as it can be observed in Figure 32 is observed in the southern and in the central part of the reservoir where the sediment thickness can reach up to 1 m. Areas with more 75 cm of sediment are rare, while areas with more than 1 m of sediment are almost inexistent.

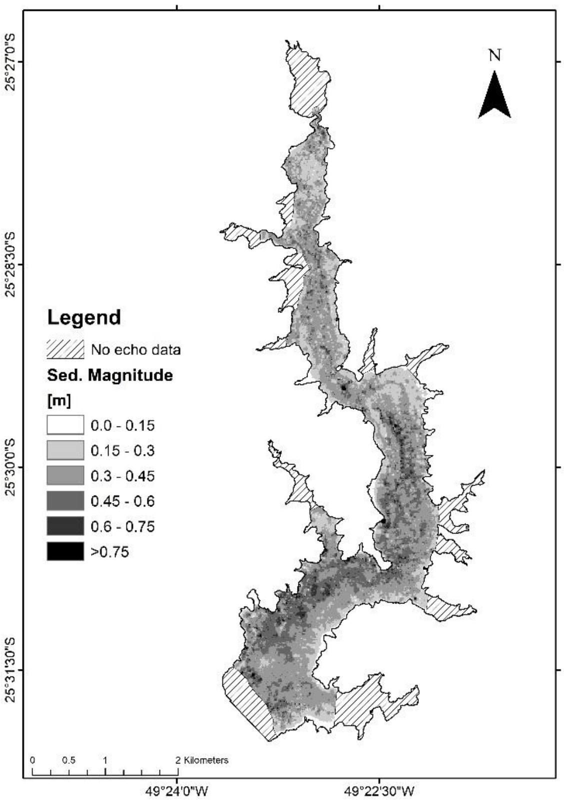


Figure 32: Sediment magnitude distribution in Passaúna reservoir, detected by the dual-frequency approach.

From this approach, it was assessed that the overall sediment accumulation was 2.47 hm^3 in 2018, where 77% or 1.9 hm^3 are deposited in the dead storage area. According to these findings the reservoir has lost 3.4% of its total volume during its 30 years of operation. This means that the reservoir has a yearly storage loss of 0.11%.

Parametric hydro-acoustic system

Due to the high anthropogenic activity in the catchment there is a high nutrient input into the Passaúna reservoir. As explained before, LOI of up to 50% was present in the sediment, which is a proxy for high organic material in the sediment. The high organic share in the sediment combined with the high temperatures occurring in the in the reservoir lead to high gas presence in the sediment (Marcon et al. 2019; Hilgert et al. 2019).

The presence of gas was also visually observed during the process of core sampling (ebullition eruptions) but also in the cores themselves. The high gas content in the sediment restricted significantly the penetration of the sound wave from the sub-bottom profiler. In areas with relatively low gas content the pre-impoundment lakebed could be detected, while in areas with high gas content the presented information was diffuse and no information about the sediment thickness could be derived (Figure 33). Due to the lack of soundwave penetration, the sediment distribution and sediment volume could not be derived with this approach.

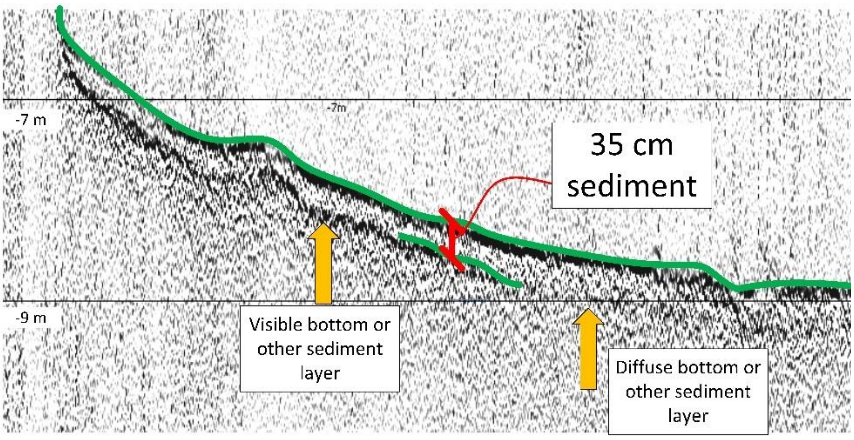


Figure 33: Limited acoustic penetration and acoustic blanking due to gas presence in the sediment.

GraviProbe

As mentioned before, in total 134 GP measurements were conducted (Figure 35a). As explained before, an abrupt change in DCPR curve slope could be linked with a change in the lake-bottom material. After analyzing the GP profiles, it was observed that at the locations where the GP had reached the pre-impoundment soil at the DCPR value of 200 kPa an abrupt change in the curve slope was observed. From this observation, it was assumed that for Passaúna's conditions, the value of 200 kPa is an orientation value for discriminating between sediment and pre-impoundment soil. Based on this approach, sediment thicknesses between 0 and 1.8 m were measured in the reservoir. The average measured sediment thickness in the reservoir was 57 cm. As it can be seen from figure x, the most important sediment accumulation areas are near the inlet of the reservoir (south of Ferraria Bridge) and near the dam reaching up to 1.8 m.

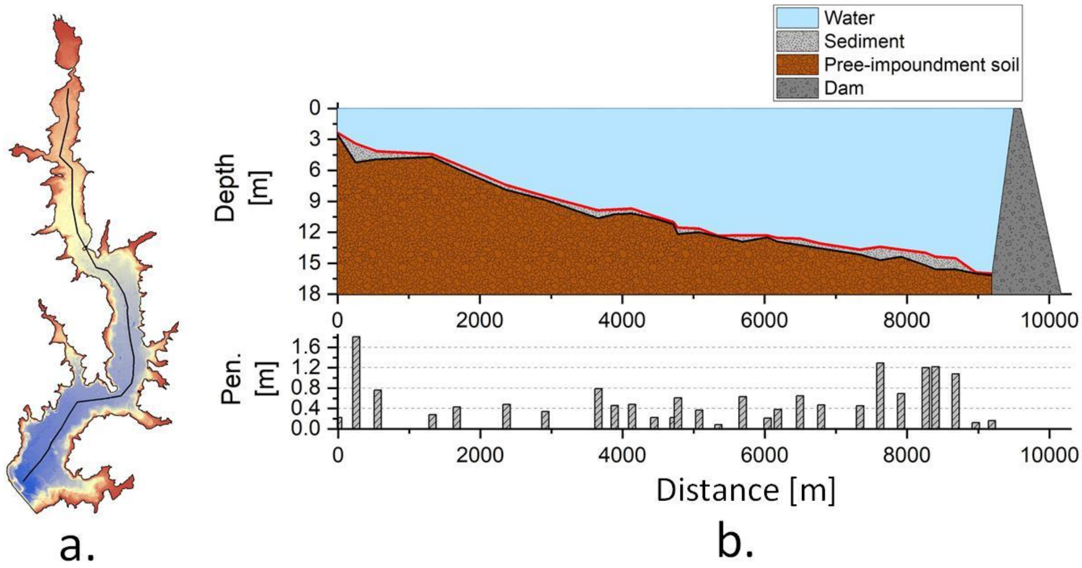


Figure 34: Longitudinal Profile of the reservoir and the sediment thickness from GraviProbe measurements

After interpolating the values, as shown in Figure 35b, in most of the reservoir, the sediment thickness is in the range of 0–0.7 m. From this map an overall sediment volume of 3.36 hm^3 was calculated, where 74% or 2.37 hm^3 are deposited in the dead storage area. The overall sediment volume corresponds to 4.6% of Passaúna's initial volume or to a siltation rate of 0.15% or 112,000 m^3 per year.

.

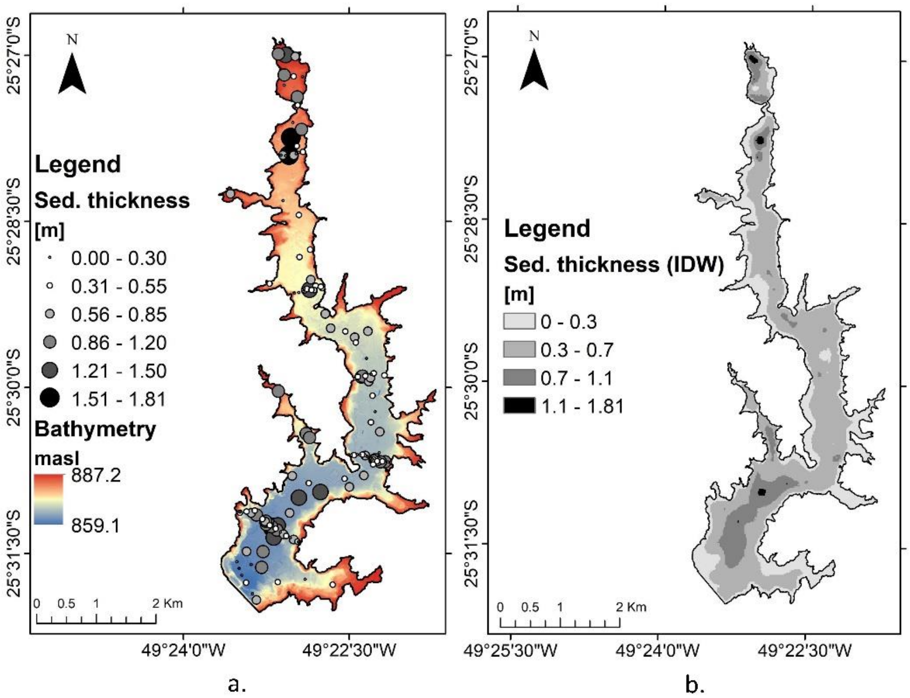


Figure 35: a. Location and sediment thickness of the measurement. b. Sediment thickness from GraviProbe measurements, interpolated with IDW.

Summary of measurement techniques

As shown also in (Table 2), all approaches carry uncertainties. Initially, these errors are associated with the accuracy of the devices. In this regard, the two devices which performed better, are the GP and the sub-bottom profilers. The linear single-beam system has clear limitations, which can produce errors up to 27% for Passaúna. As far as the overall accuracy of the measurements is concerned, the EA400 showed the highest inaccuracies. When compared to the GP results the dual frequency approach expressed a Normalized Mean Absolute Error of 56%. Interpolation is also a cause of bias in the results. Combined with the results' accuracy, the interpolation technique IDW can cause a deviation of 22.8% and 42% for the GP and EA400 measurements respectively. However, these values can differ significantly depending on the amount of points, their spatial distribution, and the interpolation technique. The other approaches could not be properly evaluated due to the lack of reference data. Concerning previous sedimentation studies of Passaúna reservoir, Saunitti et al. (2004) found sedimentation rates between 0.66–3.04 cm a^{-1}. As shown in Table 2, the sedimentation rates calculated form this project lie within the same range of sedimentation rates found from Saunitti et al. (2004) (Sotiri 2020).

Table 2: Method overview of sediment detection methods.

Method	Sediment volume (hm^3)	Mean sedimentation rate (cm/year)	Usable life (sediment until 887.2 masl)	Maximum error due to device accuracy (cm [%])	NMAE due to interpolation and device accuracy (%)
Topographic differencing via multi-beam	n. a.	n. a.	n. a.	n. a.	n. a.
EA400 - spatial information	2.47	1.2	909	9.6 [27]	42
EA400 - point information at core locations	2.70	1.07	808	9.6 [27]	n. a.
Parametric sub-bottom profiler SES2000	n. a.	n. a.	n. a.	1–5 [n. a.]	n. a.
Core samples	3.90	1.51	569	n. a.	n. a.
DFFP GraviProbe spatial information	3.36	1.9	641	1 [2]	22.8
Saunitti et al. (2004)		0.66–3.04			

n.a. – not assessable

Reservoir lifetime assessment

The findings of the sediment volume and distribution were used for the quantification of the reservoir lifetime. From the five measurement techniques used for the sediment thickness detection, four were used to assess the reservoir lifetime, while the results of multibeam and sub-bottom profiler could not be used for volumetric sediment calculations (Table 2). Under the assumption that the sediment input from the catchment will not change in the following years, it will last between 569-909 years for the full sedimentation of Passaúna. For the usable lifetime (duration until the total loss of storage capacity) estimation, we used both spatial and point information. The reservoir usable lifetime was calculated by dividing the initial storage capacity by the yearly sediment input. In the case of the spatial information (GP and EA400), the interpolated maps were used to find the overall sediment volume. Based on that, we calculated the yearly sediment input by dividing the overall sediment volume by the years of reservoir operation under the assumption that the sediment input is constant over the years. For the point information, the overall sediment volume was computed by multiplying the mean measured sediment thickness with the area of the reservoir. The overall lifetime was assessed, following the same principle as for the spatial data.

Despite the findings from Table 2 that suggest a reservoir lifetime of at least 569 years, the reservoir may suffer the problems of sedimentation earlier. By examining the GP profile at the water intake, a mean sedimentation rate of 1.85 cm/year was measured in the thalweg. When extrapolating the finding to future scenarios, assuming that the longitudinal deposition pattern in the reservoir and sediment input from the catchment will not change and no sediment remediation measures will be applied in the reservoir, it is expected that the technical structure of water abstraction will face problems before 300 years have passed (Figure 36). However, with the frequency increase of extreme events due to climate change, or the increase in internal sediment production of the reservoir, the Passaúna reservoir may encounter problems even before the predicted time.

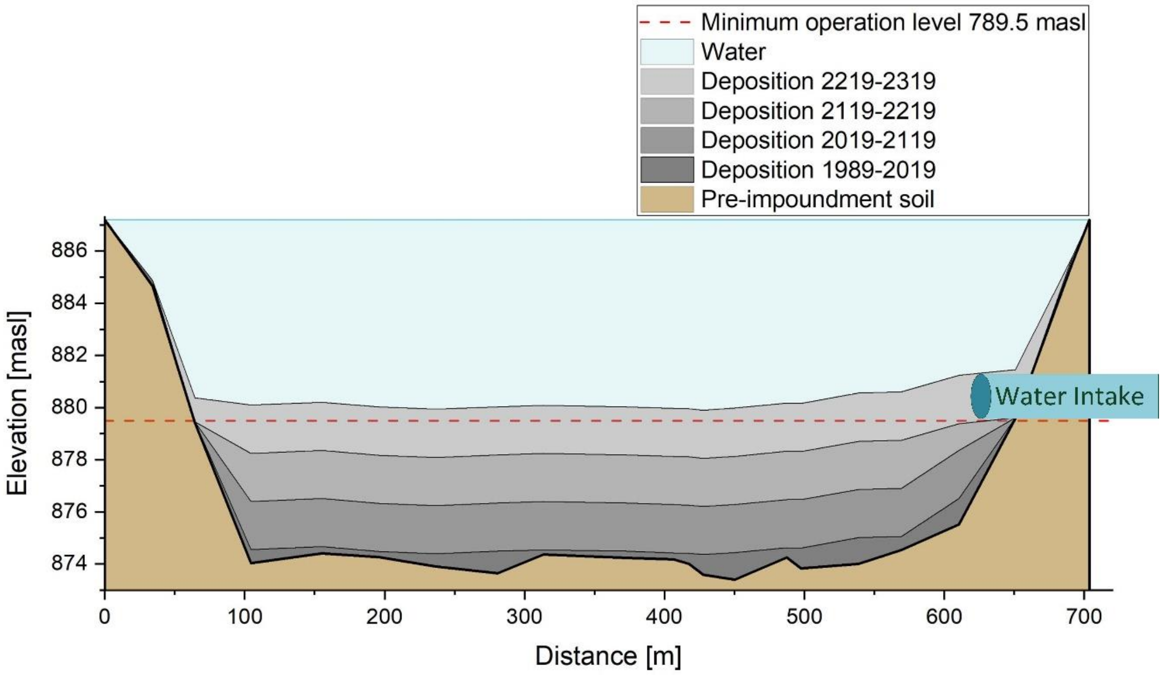


Figure 36: Predicted accumulation behavior for the Passaúna reservoir.

The project has shown, that several techniques can be applied for a precise mapping of sediment deposition in the reservoir. However, each type of reservoir needs specific surveying techniques and often the methods suggested from international guidelines are not sufficient. One major finding of this WP consists in summarizing the conclusions from each method in a compacted diagram as presented in Figure 37. The figure presents a guiding work flow on how to choose the most suitable technique for in-reservoir sediment detection techniques based on three levels of information (existence of previous bathymetric data, gas content in the sediment and expected sediment thickness). The accuracy of the measurement depends highly also on the frequency and density of the measured points from each technique. As showed in this project, the scientific solutions already exist but need to be transferred to wide engineering use. One of the main restrictions for the application of these techniques is the high costs associated with these studies (several hundreds of thousands of euros including equipment costs and human resources costs). Therefore, in order to minimize these costs, prior to any sedimentation study or survey, profound knowledge of the geomorphological characteristics of the catchment and the reservoir are needed for choosing the most suitable approach (Sotiri 2020).

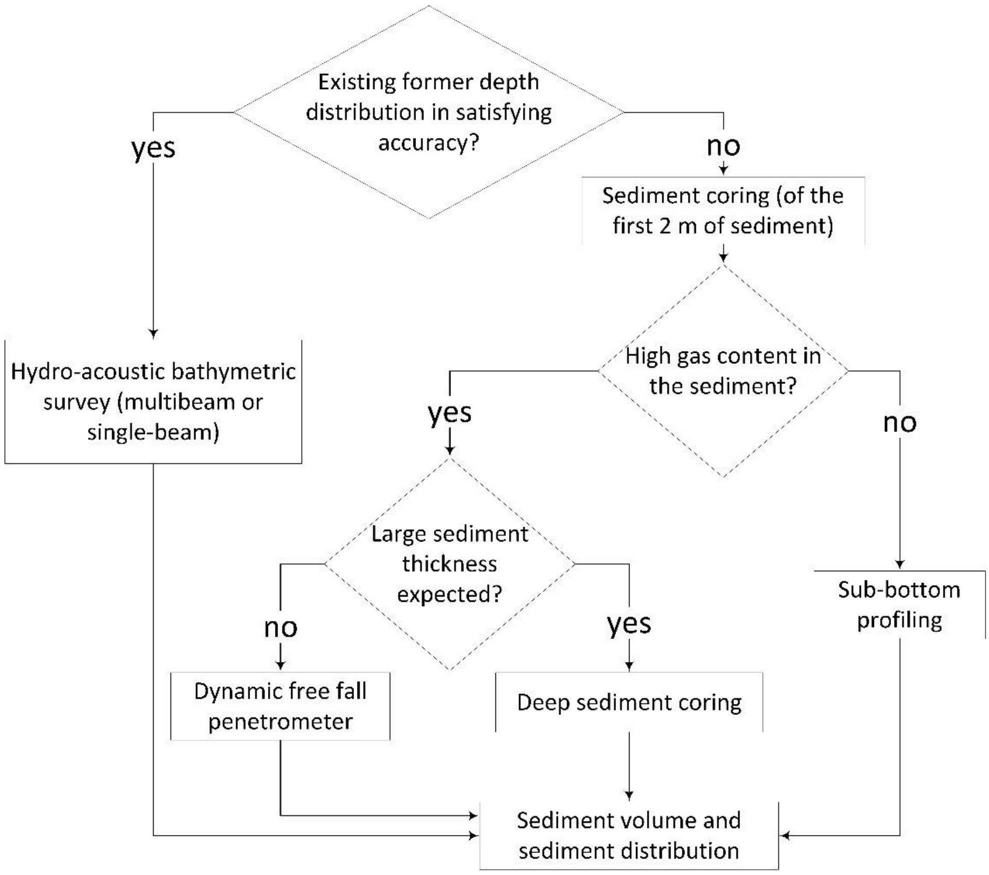


Figure 37: Work flow for an adapted sediment detection program.

References of WP1:

Albatal, Ali; Stark, Nina (2017): Rapid sediment mapping and in situ geotechnical characterization in challenging aquatic areas. In Limnology and Oceanography: Methods 15 (8), pp. 690–705. DOI: 10.1002/lom3.10192.

Alewell, Christine; Borrelli, Pasquale; Meusburger, Katrin; Panagos, Panos (2019): Using the USLE: Chances, challenges and limitations of soil erosion modeling. In International Soil and Water Conservation Research 7 (3), pp. 203–225. DOI: 10.1016/j.iswcr.2019.05.004.

Annandale, G. (2014): Sustainable water supply, climate change and reservoir sedimentation management: Technical and economic viability. In Reservoir Sedimentation; Schleiss, AJ, Cesare, GD, Franca, MJ, Pfister, M., Eds.

Annandale, G. W.; Morris, G. L.; Karki, P. (2016): Extending the Life of Reservoirs: The World Bank.

Auerswald, K. (1989): Predicting nutrient enrichment from long-term average soil loss. In Soil Technology 2 (3), pp. 271–277. DOI: 10.1016/0933-3630(89)90011-1.

Balk, Helge; Lindem, T. (2014): Sonar4 and Sonar5-Pro Post processing systems. Norway.

Basson, G. R. (Ed.) (2009): Management of siltation in existing and new reservoirs. General Report. 23rd Congress of the Int. Commission on Large Dams CIGB-ICOLD.

Bouyoucos, G. J. (1935): The clay ratio as a criterion of susceptibility of soils to erosion. In Journal of the American Society of Agronomy 27, pp. 738–741.

Bruk, Stevan (1985): Methods of computing sedimentation in lakes and reservoirs.

Carvalho, N.; Júnior, N. P.; dos Santos, P. M.; Lima, J. E. F. (2000): Reservoir sedimentation assessment guidline. BRAZILIAN ELECTRICITY REGULATORY AGENCY. Brazilia.

Central Water Commission; Central Dam Safety Organisation (2019): Handbook for Assessing and Managing Reservoir Sedimentation. New Delhi.

Gomes de Quevedo, Claudia Maria; da Silva Paganini, Wanderley (2016): Detergents as a Source of Phosphorus in Sewage: the Current Situation in Brazil. In Water Air Soil Pollut 227 (1). DOI: 10.1007/s11270-015-2700-3.

Hilgert, Stephan; Sotiri, Klajdi; Marcon, Lediane; Liu, Liu; Bleninger, Tobias; Mannich, Michael; Fuchs, Stephan (2019): Resolving spatial heterogenities of methane ebullition flux from a Brazilian reservoir by combining hydro-acoustic measurements with methane production potential. In 38th International Association of Hydro Resources World Congress Proceedings, pp. 3576–3585. Available online at https://static.iahr.org/34/418.pdf.

Innomar Technologies GmbH (2016): User's Guide ISE 2.9.5 Post Processing Software.

Kirichek, Alex; Rutgers, R. (2019): Water injection dredging and fluid mud trapping in the Port of Rotterdam. Roterdam, The Netherlands. In CEDA Dredging Days.

Kirichek, Alex; Shakeel, Ahmad; Chassagne, Claire (2020): Using in situ density and strength measurements for sediment maintenance in ports and waterways. In J Soils Sediments. DOI: 10.1007/s11368-020-02581-8.

Kongsberg Inc. (2006): EA 400 Single beam hydrographic echo sounder. Available online at https://www.km.kongsberg.com/ks/web/nokbg0397.nsf/AllWeb/5508DC01B38C35D2C12581B5004514C1/$file/160981_ea400_operator_manual.pdf?OpenElement.

Marcon, Lediane; Bleninger, Tobias; Mannich, Michael; Hilgert, Stephan (2019): High-frequency measurements of gas ebullition in a Brazilian subtropical reservoir-identification of relevant triggers and seasonal patterns. In Environmental Monitoring and Assessment 191. DOI: 10.1007/s10661-019-7498-9.

Missiaen, T.; Slob, E.; Donselaar, M. E. (2008): Comparing different shallow geophysical methods in a tidal estuary, Verdronken Land van Saeftinge, Western Scheldt, the Netherlands. In Netherlands Journal of Geosciences 87 (2), pp. 151–164. DOI: 10.1017/S0016774600023192.

Morris, Greg; Fan, Jiahua (2010): Reservoir Sedimentation Handbook (1.04).

Renard, K. G. (1997): Predicting soil erosion by water. A guide to conservation planning with the revised universal soil loss equation (RUSLE). Washington, D. C. (Agriculture handbook, 703).

Saunitti, R. M.; Fernandes, Luiz Alberto; Bittencourt, André Virmond Lima (2004): The study of Passauna's River Barrage with its reservoir sedimentation. In Boletim Paranaense de Geociências 54, p. 65–82.

Schleiss, Anton J.; Franca, Mário J.; Juez, Carmelo; Cesare, Giovanni de (2016): Reservoir sedimentation. In Journal of Hydraulic Research 54 (6), pp. 595–614.

Seifert, Annedore; Kopf, Achim (2012): Modified dynamic CPTU penetrometer for fluid mud detection. In Journal of geotechnical and geoenvironmental engineering 138 (2), pp. 203–206.

SoCo Project Team (2009): Adressing soil degradation in EU agriculture: relevant processes, practices and policies. Edited by G. Lowagie, S. H. Gay, A. Burell. Joint Research Council (JRC).

Sotiri, K.; Hilgert, S.; Mannich, Michael; Bleninger, Tobias; Fuchs, S. (2021): Implementation of comparative detection approaches for the accurate assessment of sediment thickness and sediment volume in the Passaúna reservoir. In Journal of Environmental Management.

Sotiri, Klajdi (2020): Integrated Sediment Yield and Stock Assessment for the Passaúna reservoir, Brazil.

Sotiri, Klajdi; Hilgert, Stephan; Fuchs, Stephan (2019): Derivation of a hydro-acoustic sediment classification methodology from an extensive dataset of six reservoirs. In 38th International Association of Hydro Resources World Congress Proceedings, pp. 51–60. Available online at https://static.iahr.org/34/7.pdf.

Sperling, Marcos von (2007): Wastewater Characteristics, Treatment and Disposal. London, New York: IWA Publishing (BiologicalWastewater Treatment Series, Volume 1). Available online at http://www.oapen.org/search?identifier=640137.

Stark, N.; Coco, G.; Bryan, K. R.; Kopf, A. (2012): In-Situ Geotechnical Characterization of Mixed-Grain-Size Bedforms Using A Dynamic Penetrometer. In Journal of Sedimentary Research 82 (7), pp. 540–544. DOI: 10.2110/jsr.2012.45.

Stark, N.; Kopf, A.; Hanff, H.; Stegmann, S.; Wilkens, R. (2009): Geotechnical investigations of sandy seafloors using dynamic penetrometers. In Oceania, pp. 1–10.

Sullivan, P. (2003a): Applying the principles of sustainable farming. National Sustainable Agriculture Information System (ATTRA).

Sullivan, P. (2003b): Overview of cover crops and green manures. National Sustainable Agriculture Information System (ATTRA).

Sumi, Tetsuya (2004): Reservoir sedimentation management with bypass tunnels in Japan.

U.S. Department of the Interior, Bureau of Reclamation (2006): Erosion and Sedimentation Manual. U.S. Department of the Interior, Bureau of Reclamation,Technical Service Center, Sedimentation and River Hydraulics Group. Denver, Colorado.

Vigiak, O.; Borselli, L.; Newham, L.T.H.; McInnes, J.; Roberts, A. M. (2012): Comparison of conceptual landscape metrics to define hillslope-scale sediment delivery ratio. In Geomorphology 138 (1), pp. 74–88. DOI: 10.1016/j.geomorph.2011.08.026.

Vörösmarty, Charles J.; Meybeck, Michel; Fekete, Balázs; Sharma, Keshav; Green, Pamela; Syvitski, James P.M (2003): Anthropogenic sediment retention: major global impact from registered river impoundments. In Global and Planetary Change 39 (1-2), pp. 169–190. DOI: 10.1016/S0921-8181(03)00023-7.

Wagner, Adrian (2019): Event-Based Measurement and Mean Annual Flux Assessment of Suspended Sediment in Meso Scale Catchments. Doctoral Thesis. Karlsruhe Institute of Technology, Karlsruhe, Germany.

Waltrick, Paulo Cesar; Machado, Marco Aurélio de Mello; Dieckow, Jeferson; Oliveira, Dalziza de (2015): ESTIMATIVA DA EROSIVIDADE DE CHUVAS NO ESTADO DO PARANÁ PELO MÉTODO DA PLUVIOMETRIA: ATUALIZAÇÃO COM DADOS DE 1986 A 2008. In Rev. Bras. Ciênc. Solo 39 (1), pp. 256–267. DOI: 10.1590/01000683rbcs20150147.

Wischmeier, Walter H.; Smith, Dwight David (1978): Predicting rainfall erosion losses-a guide to conservation planning. In Predicting rainfall erosion losses-a guide to conservation planning.

Yutsis, Vsevolod; Krivosheya, Konstantin; Levchenko, Oleg; Lowag, Jens; León Gómez, Héctor de; Tamez Ponce, Antonio (2014): Bottom topography, recent sedimentation and water volume of the Cerro Prieto Dam, NE Mexico. In Geofísica Internacional 53 (1), pp. 27–38. DOI: 10.1016/S0016-7169(14)71488-6.

5.1.3. Flyers

MuDak-WRM

FONA Research for Sustainable Development BMBF

Sponsored by the Federal Ministry of Education and Research

Modelling sediment input from Passauna catchment

Calcluation of monthly sediment input and long-term sediment balance in the Passauna catchment with the application of Revised Universal Soil Loss Equation and use of satellite images

Context

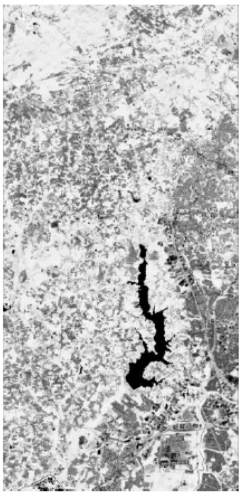
Soil loss in watersheds is a major threat to food and water security. Food supply is impaired by the degradation of fertile lands due to erosion, while water supply is restricted due to the storage loss caused from sedimentation. The major contributor in terms of soil loss and sediment input is the agricultural land. Because of the seasonal crop rotation, the agricultural areas remain a certain period of year uncovered, thus vulnerable to water erosion. As erosion is not equally distributed, spatially and teporally, detailed information about the location of erosion and sediment input hotspots is of high importance for the authorities, for managing the river basin in a proper manner.

Objectives/Goals

- Calculation of long-term sediment input budget.
- Identification of erosion and sediment input hotspots.
- Basis for watershed managing strategies.
- Increased model accuracy through inter annual resolution based on satellite data.

Methodology

For the calculation of sediment input and erosion from the catchment the Revised Universal Soil Loss Equation (RUSLE) was applied. The challenges were mainly encountered in defining a proper land cover factor for the arable land, as this factor is directly connected to the crop rotation practices and the type of crop. In this case, we used an empirical approach for calculating the C factor. For calculating the C factor the Normalized Difference Vegetation Index was used (Durignon et al. 2014). As the NDVI data had a monthly resolution, the model was able to simulate also in a monthly time step. This approach gave the opportunity to understand and simulate also the annual dynamics of sediment input from Passauna catchment. For the R factor we used the monthly factors calculated from Waltrik et al. 2015 While for the K factor a sampling campaign was organized, where 23 soil samples were taken and analyzed.



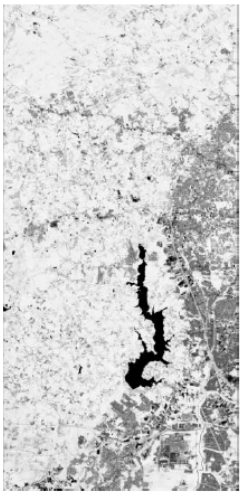
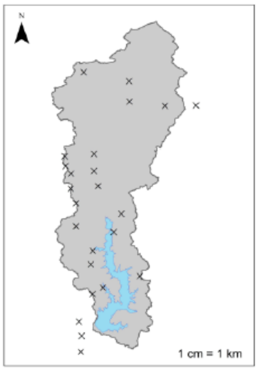


Fig. 1a. NDVI Nov.2017 Fig. 1b. NDVI Jan. 2018
Dark=no cover, Light= covered ©EFTAS



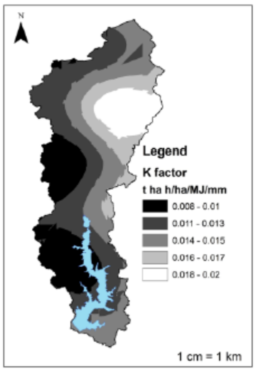


Fig. 2a. Soil sampling points Fig. 2b. K factor

Results

The spatial distribution of soil erosion and sediment input were created in a monthly basis (Fig 3). The simulated period was May 2017 until April 2018. The determining factor for soil loss is the rain intensity. The wet months are characterized by high erosion, while the dry months by low soil loss. Although the soil is covered with vegetation in the wet months the rain erosivity is rather high and creates soil erosion. In total for the simulated period the sediment yield was 70,000 ton/yr. In 30 years the total amount of sediment coming in the Passauna reservoir is 2,100,000 ton. Most of the catchment has Very slight erosion rates

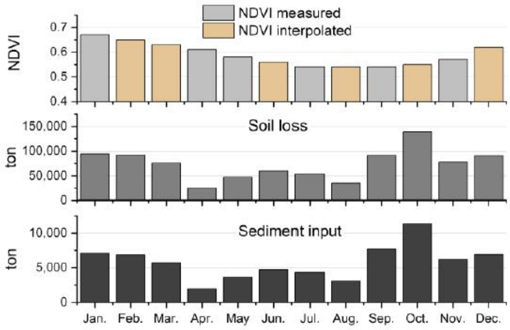


Fig. 3. Interanual dynamics of sediment input and soil loss

Table 1. Erosion classes in Passauna watershed

Soil erosion classes	% of watershed
Very Slight (<2 t/ha/yr)	55.5
Slight (2-5 t/ha/yr)	3.5
Moderate (5-10 t/ha/yr)	3.7
High (10-50 t/ha/yr)	15.8
Severe (50-100 t/ha/yr)	9.0
Very Severe (100-500 t/ha/yr)	11.3
Catastrophic (>500 t/ha/yr)	1.4

Discussion

The total amount of sediment measured with the hydroacoustic system, sediment sampling and dynamic penetrometer is 4,200,000 tons. There is a discrepancy of around 50% between the two outcomes. The difference exists partially because of a calibration error in the RUSLE factors and in part as in the RUSLE calculation the gully-channel erosion and internal production of the reservoir are not included. RUSLE is a reliable tool for order of magnitude calculations and especially location of problematic areas in the watershed. In the located hotspots several measures like contour farming, reduced tillage afforestation of agricultural areas in high slopes could be implemented.

Compared to Sauniti et al. 2004 the results show less erosion (62.7% very slight, slidght and moderate compared to 52% from Sauniti et al 2004.) The changes between the two studies are found mainly in the forested areas where the present study finds very slight erosion in contradiction to the previous one.

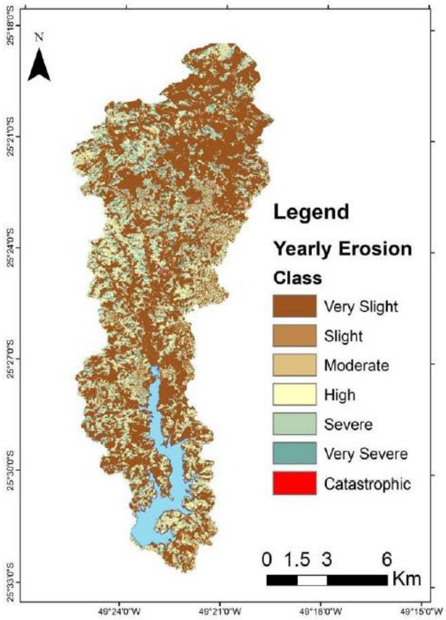


Fig. 4a. Soil erosion classes in Passauna catchment.

Innovation/Outlook

- ✓ Long-term sediment mass estimation for the operation.
- ✓ Interanual dynamics of sediment input.
- ✓ Use of remote sensing for land cover factor estimation.
- ✓ Use of the sediment input and soil loss maps for future strategical planning and sustainable management of the waterscheD.

Authors Sotiri, K.; Hilgert, S.; Duraes, M.; Wolf, N.; Armindo, R.; Fuchs, S. Contact klajdi.sotiri@kit.edu
Funded by Federal Ministry of Education and Research, BMBF Web www.mudak-wrm.kit.edu

MuDak-WRM

FONA Research for Sustainable Development BMBF

SPONSORED BY THE Federal Ministry of Education and Research

Monitoring sediment and phosphorous flux using composite sampling in Passaúna river

Monitoring of sediment and phosphorus transport in the Passauna river using composite and discrete sampling up-stream of the reservoir.

Context

The high spatial and temporal variability of river water quality of can lead to large uncertainties for the environmental protection planning and water management. River monitoring is important in order to detect short-term changes and long-term trends in water quality status. For the calibration of mass flux models for watershed management the monitoring data is essential. The main approach for reducing these uncertainties is to chose a suitable sampling strategy. A restriction thus for long-term monitoring are the costs of sampling and analyse of the samples. Composite sampling is a cost effective alternative as it is integrating many single samples in a composite sample. The composite sampling was used to assess the transported sediment and phosphorous mass over more than one year.

Objectives/Goals

- Quantification of the long-term sediment and Phosphorus input to Passaúna Reservoir
- Better understanding of the seasonal dynamics of the river fluxes
- Validation and calibration of mass flux modelling results from Passaúna catchment
- New cost-effective sampling strategy

Methodology

The flow proportional composite sampler (LVS) was installed at the Passaúna River, upstream of the PU reservoir.

After each 8000 m³ of discharge a sample of ~20 L was pumped into the tank until 1 m³ was full. The filling of tank took between 10 and 3 days. The resulting composite sample in the tank was analyzed in two components: settled material from the tank bottom (Sed) and supernatant water (SW). After dividing both components, the sediment grainsize distribution was determined and the total Phosphorus (TP) content analyzed for the <0.63 µm fraction. Also the contents of solids and phosphorous in the supernatant water were determined. Additionally, one grab sample from the river was taken each time the tank was emptied.

Afterwards the amount of sediment and Phosphorous can be calculated for each sampling period.

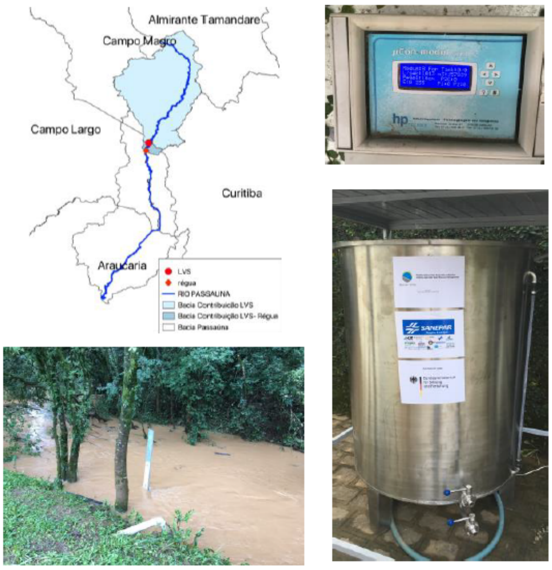


Fig.1. Overview from the LVS (location and installation)

The tank concentration is the average concentration in the I sampling period and was calculated as:

$$C_i = \frac{\text{Sed} + \text{SW}}{\text{Tank volume}} = \frac{\text{Mass}_{\text{Sed},i} + (C_{SW}{*}\text{Vol}_{SW})_i}{\text{Tank\_volume}_i}$$

The load in the sampling period was calculated as:

$$\text{Load}_i = Q_{\text{total},i} x C_i$$

Where Q total is the toal water volume that flows in the river during the ith period.

Results

The monitoring in the Passauna river started Februar 2018 until January 2020 there are 33 composite samples and 40 grab samples. Figure 2 a and b shows the results of total phosphorus (mg/l) and suspended solids (mg/l). The suspended solids concentration showed

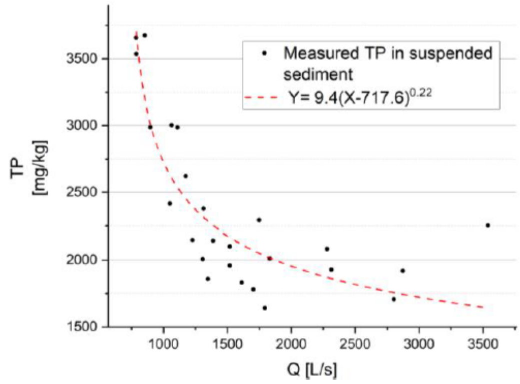


Fig. 2 Relation between average Q during a sampling period of LVS and the TP content of the suspended sediment in (mg/kg)

an increasing trend with increased discharge while the TP showed decreasing values with increased discharge.

This trend in the TP input (Figure 2) can be attributed to the high input of TP from urban areas in case of low flow conditions and from arable land through erosion in case of the mid flow conditions.

The TP results imply that the TP input from the point sources is rather important in terms of eutrophication as the TP for urban areas is easy available for the microorganisms to consume. By a simple balance for the monitoring period it was calculated that from the baseflow there was an input of 3.7 ton of TP. The grab sampling showed rather uniform results with the values fluctuating from 0 until 0.10 mg/l TP with some sporadic high values.

Discussion

During the samling period, it was rather problematic to sample the high flow events. The problem were mainly technical related (regarding pumping equipment) and not to the efficiency and reliability of the whole system itself. For having a representative sampling, important would be to have a number of samples for high flow conditions. The sampling of high flow conditions could make it possible to derive the actual mass flux also from the agricultural areas (erosion and surface runoff)

Innovation/Outlook

- ✓ Increased temporal resolution in river water quality monitoring
- ✓ Precise estimation of mass flux
- ✓ Location of relevant pathways

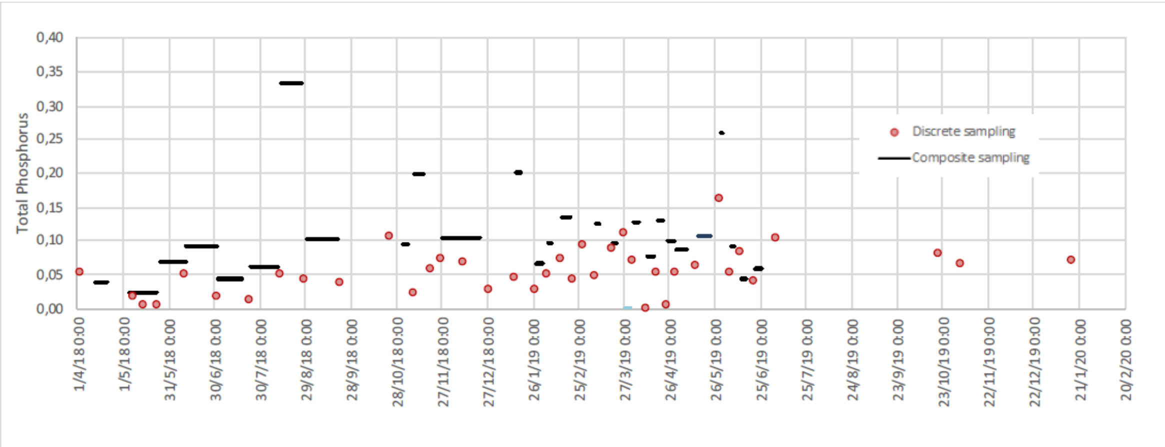


Fig. 3 Overall results from LVS monitoring

Authors Kishi, R.; Grochoki, P.; Hilgert, S.; Sotiri, K.; Fuchs, S.
Contact rtkishi.dhs@ufpr.br

Funded by Federal Ministry of Education and Research, BMBF
Web www.mudak-wrm.kit.edu

MuDak-WRM

FONA Research for Sustainable Development BMBF — Sponsored by the Federal Ministry of Education and Research

Hydro acoustic storage volume assessment

Actualization of the storage volume and surface–volume relation.

Context

For the operation of all types of reservoirs the knowledge of the exact storage volume is a crucial information. During changing environmental conditions, like floods and draughts, but also land use changes in the catchment, the necessity for adapted operation of reservoirs can be eminent.

As a basis of such operational measures lies the actual and profound knowledge of the contained amount of water. The surface–volume relation derived from the bathymetric 3D–model of the reservoir, can tell the operator, which volume relates to which level in the reservoir. Without knowing the exact amount of available water, the vulnerability during extreme events increases significantly.

Objectives/Goals

- Assessment of actual storage volume
- High definition morphological map
- Derivation of a surface–volume curve

Method and Equipment

Initially a high resolution bathymetry was created using a WASSP F3Xi multibeam echo sounder with 160°kHz, 224 single beams and an opening angle of 120° resulting in a swath width of ca. 3 times the water depth. The multibeam was combined with a Hemisphere V123 Compass for location and heading information and with a WSP–038 IMU unit for Roll/Pitch (0.25° accuracy) and heave (5°cm accuracy) correction. The system allowed for a vertical resolution of ±2°cm and horizontal resolution of ~20°cm. Since the outer beams of each multibeam system tend to produce more measurement errors than the inner beams, the driven lines are so close that the footprint of the last line is covered by 50% by the next footprint. In that manner the entire area is covered by inner beams at least once. The entire survey took ~50 hours on the boat (ca. 300°km of boat tracks) and created 1000 GB of data. For the post processing and creation of maps 60 hours were needed.

-----------Seitenumbruch-----------

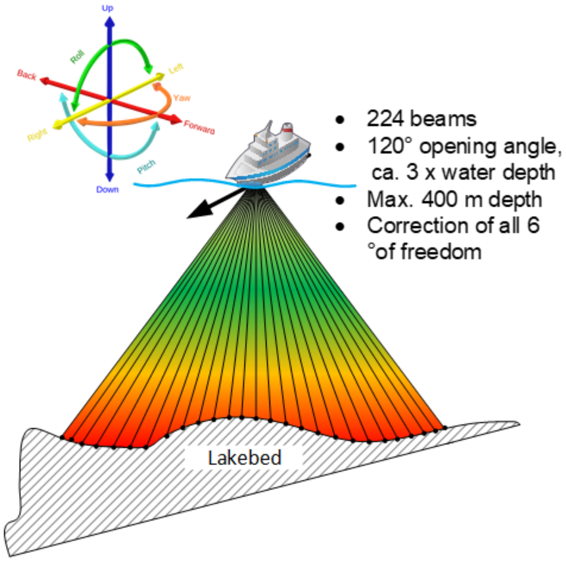


Fig. 1. Setup of the acoustic measurement system

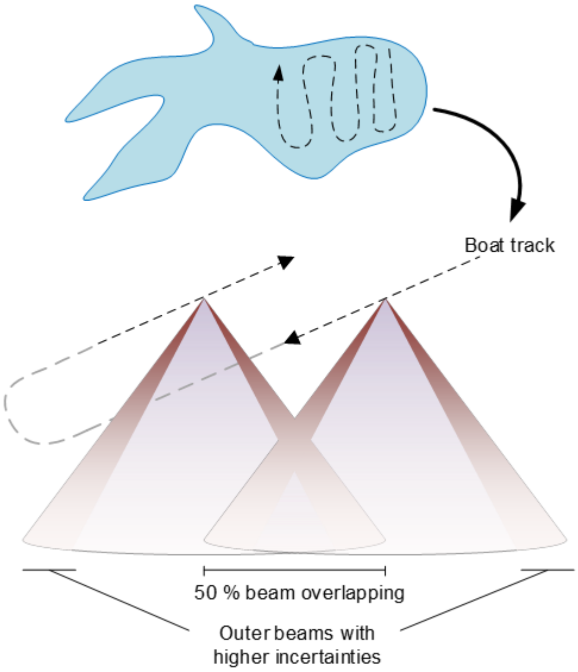


Fig. 2. Beam overlapping to increase bathymetric data quality

Results

The results of the bathymetric survey show the morphology of the actual lake bottom in high resolution (Fig. 3 & 4).

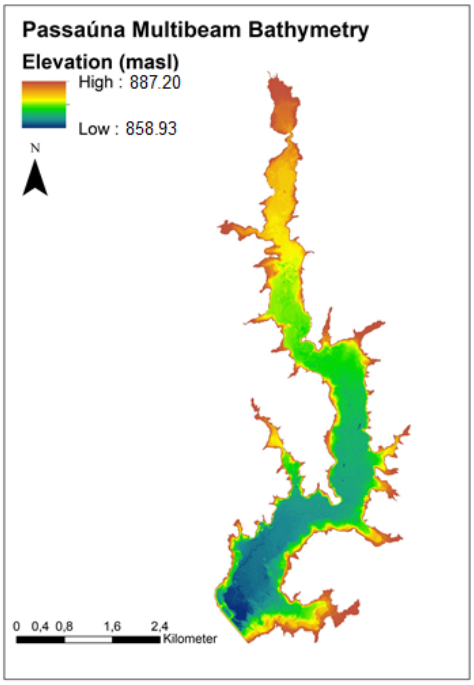


Fig. 3. Bathymetric map of Passaúna reservoir with a 20x20 cm resolution.

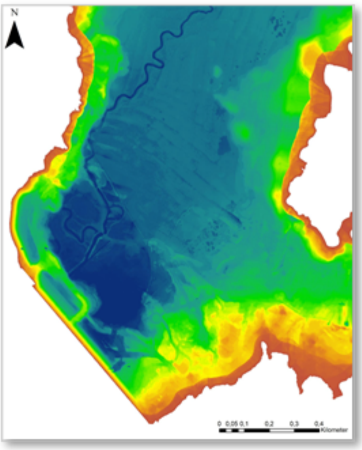


Fig. 4. High resolution map of the area in front of the Passaúna dam.

We derived a 3D model from the bathymetric measurements and calculated the water level–volume relation (WLVR) for maximum water level. The actual volume of the Passaúna reservoir is 70,094,400 m³ at a level of 887.2 masl. From the SVR you can see that with a draw down of 4 m the volume is reduced by ~42%.

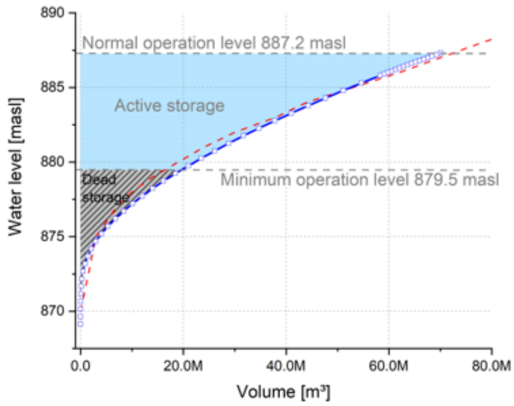


Fig. 5. Water level–Volume Relation (WLVR) for the Passaúna reservoir (blue line) in 2019. The storage volume was calculated for each 10 cm for the upper 2 m, and each 1 m for the rest of the water level (blue squares). The red lines shows the old SVR before impoundment (Source: Sanepar).

Discussion

The results show the direct value of a bathymetric multibeam survey. The morphological information might be usefull for any type of sampling or contruction work in the reservoir. As the actual storage volume and especially the WLVR were actualized, we recommend to use this data, which allows the operator to manage the reservoir during extreme situations. Additionally, a repeated survey or a combination with sediment detection may give valuable predictions for the life time of the reservoir (see Flyer on Sedimentation).

Innovation/Outlook

- ✓ High precision storage volume assessment.
- ✓ Basis for future siltation rate calculations.
- ✓ Secure long-term planning for the reservoir operator.

Authors Hilgert, S.; Sotiri, K.; Fuchs, S. Contact stephan.hilgert@kit.edu
Funded by Federal Ministry of Education and Research, BMBF Web www.mudak-wrm.kit.edu

MuDak-WRM

FONA Research for Sustainable Development BMBF — Sponsored by the Federal Ministry of Education and Research

Sedimentation in Passauna reservoir

Hydro acoustic measurements for the creation of bathymetry, and detection of sediment charactersitics and sediment mass.

Context

The construction of dams always causes a disruption of ecosystems and a massive change in the local and regional environment and their related ecosystem services. The previously transported organic and inorganic material stays within the reservoir up-stream of the dam, settles and accumulates as sediment. One consequence is the loss of storage volume. This storage volume loss leads to an increased vulnerability of the reservoir operation (e.g. during draughts). Due to a lack of sediment information (quality and quantity), the management options for the responsible operators are strongly limited. Improved sediment information about exact location and mass of sediment in the reservoir would provide critical insights for short- and long-term decision making and hazard prevention.

Objectives/Goals

- Assessment of actual storage volume
- Definition of sedimentation rate
- Spatial distribution of sediment thickness
- Calculation of storage volume loss

Method and Equipment

The sediment was ensonified using two single beam echosounders. The combination of the EA400 (Kongsberg) with 200 & 38 kHz and the SES 2000 compact (sub-bottom profiler, Innomar) with adjustable 4 to 12 kHz allows for the collection of detailed acoustic information of the sediment (Fig.1). Together with sediment samples (cores and grabs), which are analysed in the laboratory for sediment density. All information is stored with high precision GPS reference. For validating the hydroacoustic measurements, apart from the core sampling, also a dynamic penetrometer (GraviProbe GP) was used at around 130 locations to measure the sediment thickness. The GraviProbe is a heavy dart equipped with pressure and acceleration sensors. It can penetrate the sediment until the first strongly consolidated layer. Using the GraviProbe, transversal as well as longitudinal profiles of Passauna Reservoir were collected (Fig. 2).

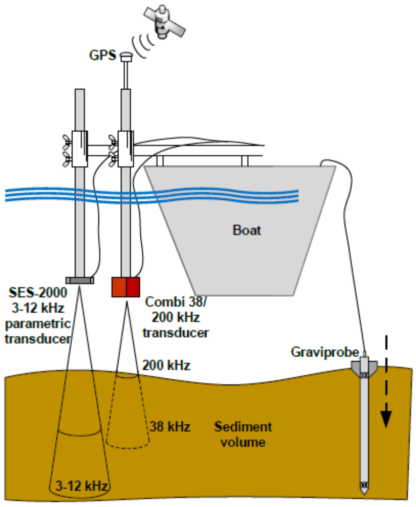


Fig. 1 Setup of the acoustic measurement system and application of the GraviProbe

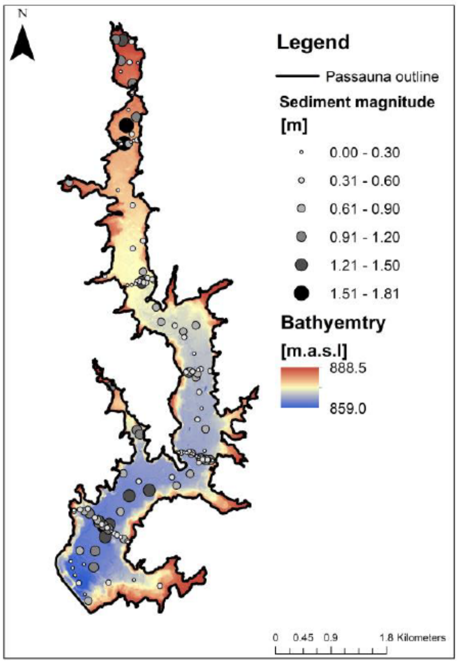


Fig. 2. Locations of GraviPrope measurements with sediment magnitude at the corresponding location, multibeam bathymetry in the background

Results

According to the EA400 results the deepest spots of the reservoir is the area with the highest sediment accumulation. In these parts of the reservoir the sediment thickness reaches around 1 meter and in some cases until 1.6 m. The shallow areas of the reservoir seem to have a lower sediment accumulation, reaching values until 0.6-0.7 m. In total at least 3,700,000 m³ (0-4 cm/year) of the total volume is lost due to sedimentation based on acoustic measurements. This corresponds to a volume loss of around 5%. The validation measurements with the penetrometer show a volume loss of 3,400,000 m³ (0-6 cm/year). Especially the maximum sediment thickness in the deep part was almost twice the sediment thickness derived from the hydroacoustics. In the shallow parts, the GraviProbe measurements prove the presence of high sediment thickness at specific locations but not in the entire coverage of the reservoir as the hydroacoustics show.

Discussion

Comapred to the overall reservoir sedimentation rate in the world(~1% per year) Passauna has a rather small sedimentation rate. However this study indicated that the sedimentation rate is larger than previously calculated from Sauniti et al. 2004 (up to 3 cm/year)

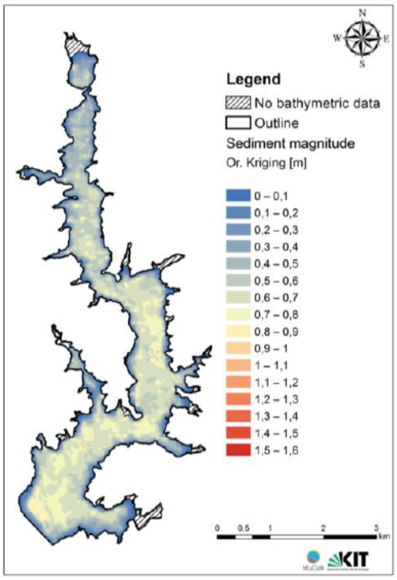


Fig. 3. Spatial distribution of sediment thickness in the reservoir from hydroacoustic measurements

Regarding the discrepancies in the results of hydroacoustics and GraviProbe, the main reason seems to be the high gas content in the sediment, as the gas is creating a barrier for the sound waves limiting penetration. Especially in the deepest parts this effect is evident. Furthermore, in the sediment budget of the reservoir, the sediment volume of the inflow part of the reservoir

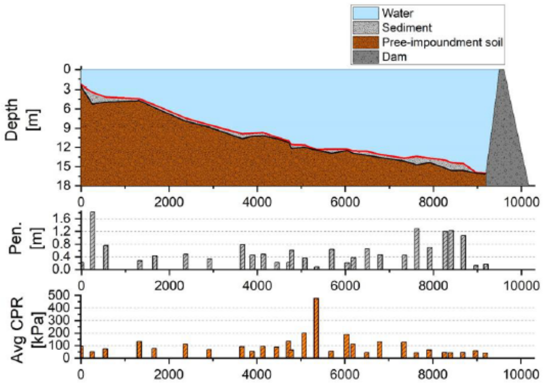


Fig. 4. Longitudinal profile of sediment thickness (top), penetration depth of graviprobe (middle), and hardness (down) in Passauna reservoir

(buffer) is not included. Precise measurements of sediment thickness in such a large spatial scale are challenging. Therefore a combination of techniques is needed for increasing the performance. Despite the mentioned errors, we managed to calculate a sediment budget of the reservoir with satisfying accuracy.

Innovation/Outlook

- ✓ High precision sediment mass estimation
- ✓ Improved information for dredging or remobilization measures
- ✓ Potential use of dredged sediments can be assessed, e.g. construction material, fertilizer
- ✓ Reduced costs for all underwater measures
- ✓ Secure long-term planning for the reservoir operator
- ✓ Use of the sediment input and soil loss maps for future strategical planning and sustainable management of the watersched

Authors Sotiri, K.; Hilgert, S.;Fuchs, S.
Contact klajdi.sotiri@kit.edu

Funded by Federal Ministry of Education and Research, BMBF
Web www.mudak-wrm.kit.edu

MuDak-WRM

Assessment of sedimentation for reservoirs

Sediment traps help to investigate the sedimentation rate as well as its spatio-temporal variation of settling particles. They represent a low-budget alternative to investigate sediment quality.

Context

Loss of storage volume and the accumulation of nutrients due to siltation threatens drinking water supply. The amount of sediment input and internal production (plancton growth) determines the sedimentation rate, which is highly important indicator for reservoir management.

Objectives/Goals

- Determine sedimentation rates in the water columm;
- Obtain its spatio-temporal variation;
- Obtain the nutrient content of settling particles;
- Compare sedimentation rates with another methods;
- Estimate the life time of the reservoir.

Method and Equipment

The sediment traps consists of two vertically arranged transparent PVC tubes. They contain two overflow plastic hoses and two sample bottles at the bottom. The vertical pipes have an internal diameter of 86 mm (Figure 1). To prevent particles from resuspending inside the bottles the length of the tubes needs to be at least 5-times the diameter of the tubes. Sample bottles are easy to change and collect. The captured material was wheighed and analyzed for Organic Matter, Total Phosphorus and Nitrogen which were determined by the KIT. The different parameters were set in relation to the distance from inflow and collection time.

Five sediment traps were installed in 2018, two of these were installed at the surface at the “intake” and “dam” location, three were placed close to the bottom (intake, dam and park locations). The difference between the surface (SUR) and the bottom (BOT) helps to understand local production processes. In 2019, all sediment traps were placed one meter above the bottom (Figure 2). As for the two surface traps, one was relocated to the southern side arm and the other one at the entrance of the Passaúna river, south of the bridge.

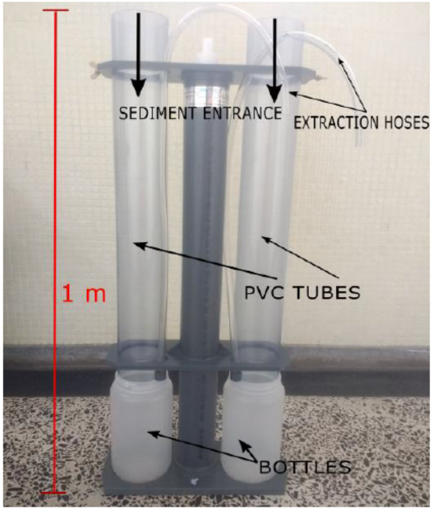


Figure 1 Sediment trap setup.

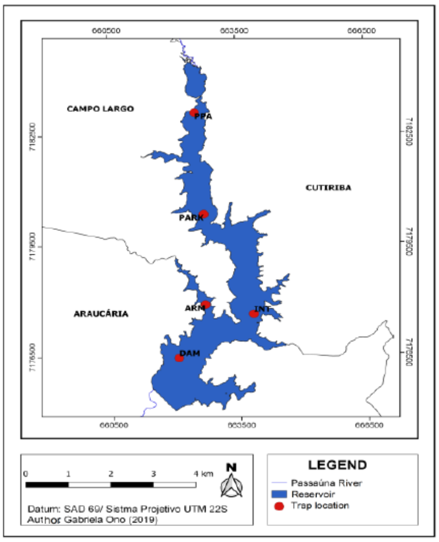


Figure 2 Locations of the sediment traps in Passaúna reservoir.

Results

Downstream of the Ferraria Bridge the sedimentation rates are extremely high with ~180,000 mg/m²/d equaling ~227 cm of sediment accumulation. They decrease over the distance from the inflow down to 1,500 mg/m²/d, ~1.9 cm sediment accumulation (Figure 3). By the differences between the samples the seasonality of sedimentation rates at the locations can be observed. Especially in the middle part of the reservoir the seasonal changes seem to be large. Close to the dam the relative changes are large, however the absolute changes of the deposited mass are low.

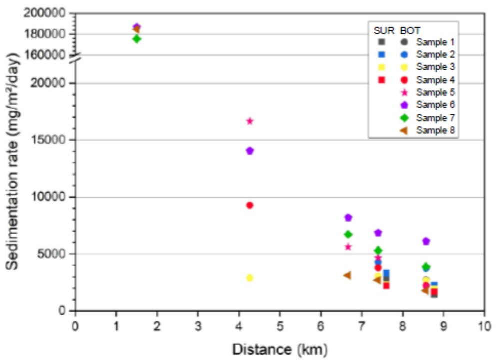


Figure 3 Longitudinal sedimentation rate variation over distance from inflow.

The weighted average sedimentation rate was 20,216 mg/m² • d, this equals 0,8 cm/yr. This rate is in the interval proposed by Sautini et al., (2004) (0.66-3.04 cm/yr).

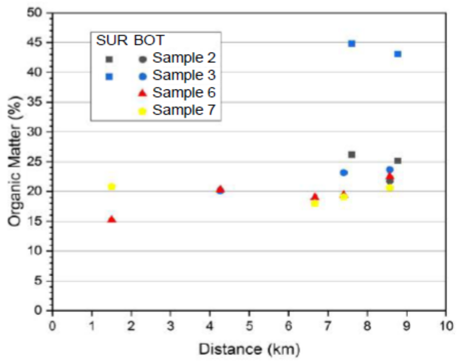


Figure 4 Organic matter content of settled material from inflow to dam.

In contrast to the decreasing sedimentation rates closer to the dam, the organic share of the settling particles increases with distance to the inflow (Figure 4). It increases from ~15% to ~25% at the bottom close to the dam. Surface samples show significantly higher organic matter shares (up to 45%).

The N/P ratio shows that Total Phosphorus as a limiting nutrient. P_T average deposition was 3,25 mg/m² • d (Figure 5) and N_T average deposition stream found was 26,4 mg/m² • d.

Figure 5 shows the temporal variability of the settling rates. In accordance with the land cover change we can see that in March to September the sedimentation rates increase (see Flyer "sediment input modelling"). This effect is mostly prevalent in the middle and lower area close to the dam.

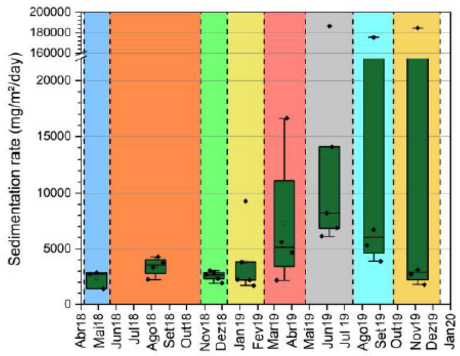


Figure 5 Temporal variation of sedimentation rates.

Innovation/Outlook

- ✓ Cheap and simple methodology for sedimentation rate assessment.
- ✓ Robust sediment mass estimation at single locations.
- ✓ Secure long-term planning for the reservoir operation.
- ✓ Important information for process understanding in combination with with other mesurements of sedimentation as Echo-bathymetry, GraviProbe data and Core data.

Authors Ono, G. M.; Mannich, M.; Hilgert, S.; and Bleninger, T. Contact stephan.hilgert@kit.edu
Funded by Federal Ministry of Education and Research, BMBF Web www.mudak-wrm.kit.edu

5.2. Work package 2 – Water balance model

5.2.1. Introduction and objectives

Any reservoir's water quantity and water quality is strongly depending on the water balance of its catchment. Thus, an adequate water balance model (WBM) is an essential tool for reservoir management. Such a WBM can be used to supplement discharge (and river water temperature) observations in time and space, to plan and manage a reservoir with respect to water quantity, to asses possible future changes by running scenarios and for real-time short-term forecasting of the inflow into the reservoir. Moreover, a spatially distributed WBM is also an important basis for modeling diffuse emissions of nutrients and contaminants within the catchment. Therefore, we used the process-oriented, spatially distributed WBM LARSIM within this project. LARSIM simulates all relevant aspects of the terrestrial water balance, including interception, snow dynamics, infiltration, evapotranspiration, soil water balance and runoff generation, runoff concentration, river routing, reservoir retention etc. (LEG 2020). Runoff generation can be modelled on the scale of small Hydrological Response Units (HRU), which allows quantifying the contribution of different flow paths (components) to total discharge in a spatially distributed way. This is an important improvement for assessing and predicting diffuse emissions with emission models such as MoRE (LUBW 2017). Furthermore, LARSIM can also be used to simulate and project river water temperatures on a physical basis (Haag & Luce 2008, Haag 2018).

Hence, the primary objective of WP2 was to setup and apply LARSIM models for the catchments of the drinking water reservoirs Große Dhünn (Germany) and Passaúna (Brazil). The models should supply the necessary hydrological input to the other WPs (e.g. emission modeling, hydrodynamic modeling). Mainly the Passaúna model should also be applied to shed some light on site-specific problems in order to exemplify the usefulness of water balance modeling in the context of reservoir management. Finally, the state-of-the art model for the Große Dhünn should be simplified gradually, in order to find minimum requirements of a WBM for different applications.

5.2.2. Preparation and method

The present study deals with the catchments of the drinking water reservoirs Große Dhünn in Germany and Passaúna in Brazil (Figure 38). The Große Dhünn catchment is situated in western Germany in the temperate climate zone (latitude: 7.2° and longitude: 51.1°). Mean air temperature is approximately 10.3 °C and mean yearly precipitation approximately 1100 mm The natural catchment of the reservoir comprises 60 km^2, but additional water is diverted into the reservoir from the neighboring catchment of the Kürtener Sülz (29 km^2) (Krumm & Haag 2019). The Passaúna catchment is situated in the tropical to subtropical region of southern Brazil near the city of Curitiba (latitude: −25.5° and longitude: −49.1°). The catchment of the reservoir covers an area of 143 km^2. Mean air temperature is approximately 18.7 °C and mean yearly precipitation approximately 1650 mm (Krumm et al. 2019).

We setup a LARSIM WBM for the catchment of the Große Dhünn reservoir, including the neighboring catchment of the Kürtener Sülz (diversion) and the catchment of the Dhünn downstream of the reservoir. To do so we used a high resolution digital soil map (BK50) and ATKIS Land Cover data of the federal state of North Rhine-Westphalia (Krumm & Haag 2019). These data were also used to derive spatially distributed parameters for the newly implemented, physically based infiltration module of LARSIM (e.g. Haag et al. 2019; Steinbrich et al. 2016). The model thus uses the most sophisticated and data demanding LARSIM module for runoff generation. It is generally forced by data from meteorological stations in an hourly time step. However, to analyze events with high rain intensity, which are particularly relevant for nutrient emission and soil loss from agricultural surfaces, the model may also be run in shorter time steps (e.g. 5 minutes), also using radar data as precipitation input. The LARSIM WBM for the Große Dhünn can thus be seen as a state-of-the-art model, which serves as a reference for model simplifications.

We also setup a LARSIM WBM for the Passaúna, including the catchment downstream of the reservoir until the confluence with Iguazu River. In this case, spatially distributed land cover data and parameters for the evapotranspiration module were derived from remote sensing data by our project partner EFTAS (Krumm et al. 2019). Since no adequate soil data were available, the department of soil science (Prof. Armindo) of the Federal University of Parana (UFPR) analyzed 11 topsoil samples with respect to grain size distribution and hydraulic properties. We used these data to derive effective pore volume and plant available field capacity as parameters of the LARSIM soil module. However, it was not possible to derive a reliable spatial distribution of these parameters. Therefore, in the case of Passaúna, we applied a relatively simple soil module for runoff generation with spatially uniform soil properties only. The model is forced by data from meteorological stations. Due to limitations with respect to temporal resolution of these data, the model runs in a daily time step. The Passaúna model can thus be viewed as a relatively simple LARSIM model with moderate data demand, which is representative for the complexity that may typically be achieved anywhere in the world (Krumm et al. 2019). In the case of Passaúna, we also applied the water temperature module of LARSIM, which allows simulating the river water temperatures on a physical basis (Haag & Luce 2008).

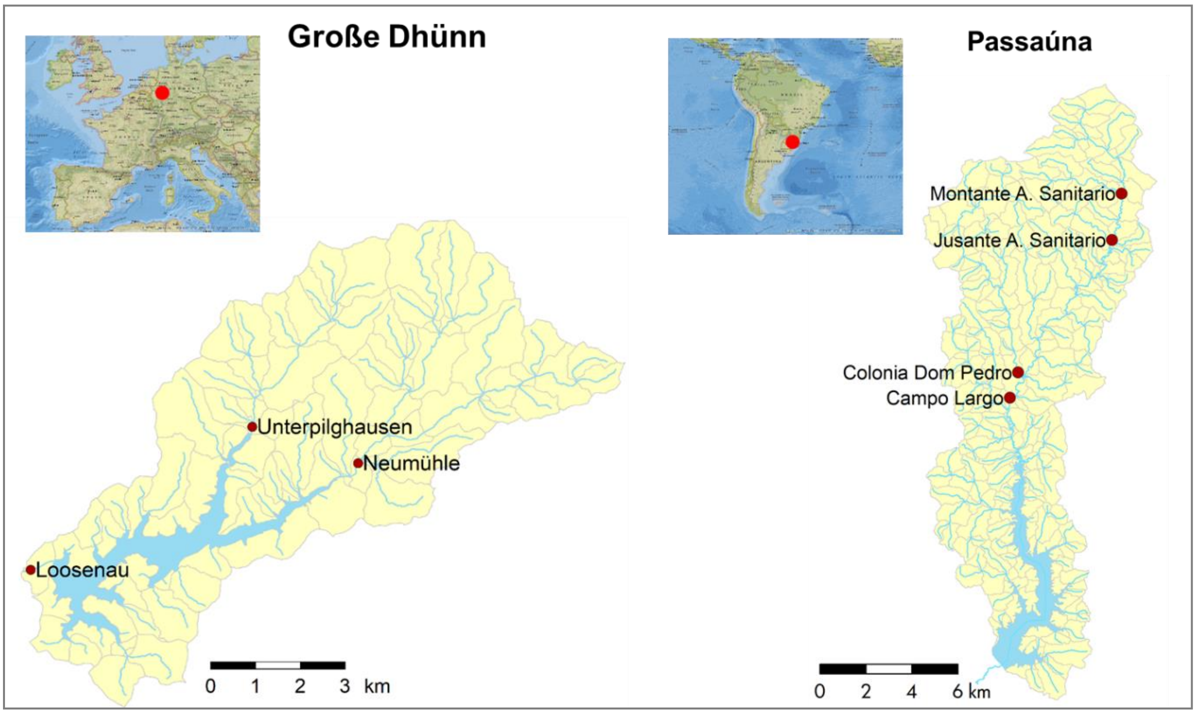


Figure 38: Overview of the location and river network of the two study sites, including locations of hydrological gauges. (Source of Background map: National Geographic, Esri, Garmin, HERE, UNEP-WCMC, USGS, NASA, ESA, METI, NRCAN, GEBCO, NOAA, increment P Corp.)

5.2.2.1. Validation

The LARSIM models for both catchments were calibrated and validated with measured discharges of several gauges. For the Große Dhünn, the same calibration parameters could be applied to the three sub-catchments upstream of the reservoir, indicating that the spatial differences of the hydrological reaction is well mapped by the spatial distribution of the physically based parametrization (i.e. land cover, soil, etc.). Despite relatively small catchment sizes of 11 and 21 km^2, discharge simulations corresponded very well with measurements (Table 1, Figure 2). In addition, also the temporal dynamics of the reservoir volume and the surface runoff created by a heavy thunderstorm in the catchment of the Kürtener Sülz could be simulated well (Krumm & Haag 2019; Haag et al. 2021).

Table 3: Results of calibration for two gauges in Große Dhünn catchment. “Ref” refers to reference values, i.e. for measures of fit the best theoretically possible value, for all other measures the value deduced from measured discharge. “Sim” refers to the simulation results. (r^2 = Pearson’s R^2, NSE = Nash Sutcliffe efficiency, NSE ln = NSE of logarithmic discharge, balance = (Sum Qsim) / (Sum Qmes), MNQ = mean low flow, MQ = mean flow, MHQ = mean high flow, BFI = Baseflow index)

		r²	**NSE**	**NSE ln**	**balance**	**MNQ**	**MQ**	**MHQ**	**BFI**
		[-]	[-]	[-]	[-]	[m³/s]	m³/s	m³/s	-
Neumühle	Ref	1.00	1.00	1.00	1.00	0.06	0.53	7.4	0.25
	Sim	0.87	0.85	0.79	1.02	0.07	0.54	7.0	0.24
Unterpilghausen	Ref	1.00	1.00	1.00	1.00	0.04	0.28	3.6	0.24
	Sim	0.84	0.82	0.77	0.98	0.04	0.27	3.5	0.25

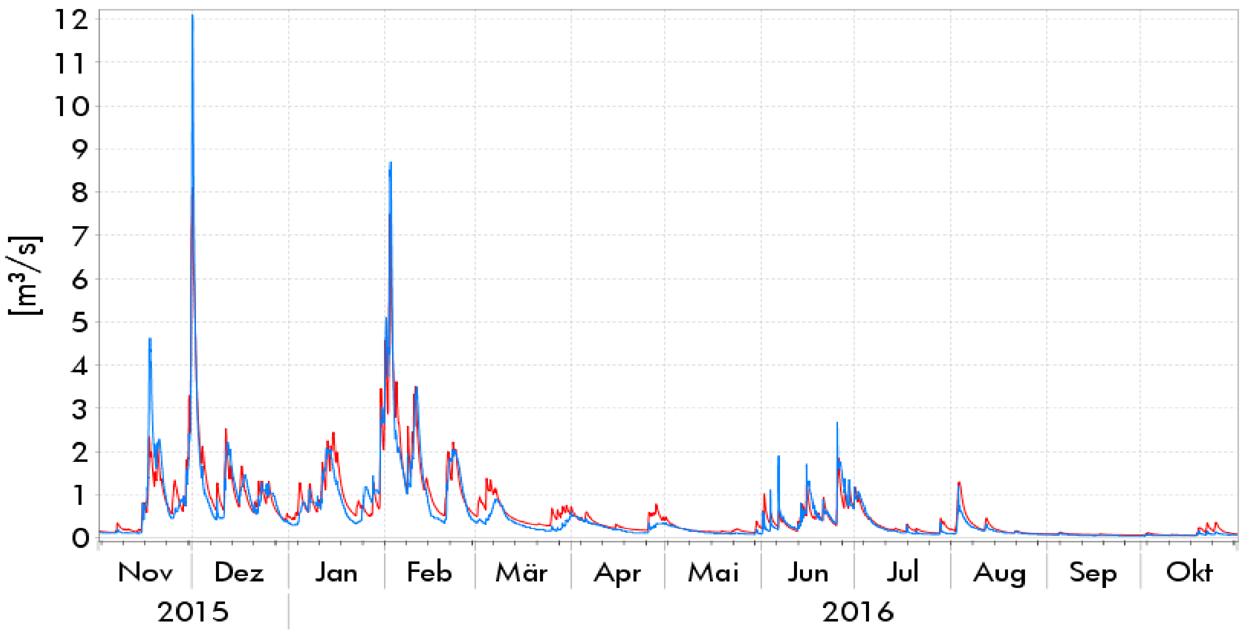


Figure 39: Simulation result for hydrological year 2016 at gauge Neumühle / Große Dhünn (blue: measured discharge, red: simulated discharge).

For the Passaúna catchment, different calibration parameters had to be applied to each of the four gauged sub-catchments to yield good results for discharge. Hence, in this case, the spatial differences of the hydrological behavior had to be achieved by calibration, most likely because no spatially distributed soil data could be used. Still, the simulation of the hydrographs yielded satisfactory results (Table 2, Figure 3) (Krumm et al. 2019). In contrast, the observed volume of the reservoir could not be matched with the simulations. However, we showed that this was due to errors in the data of the reservoir outlet (see next section). Furthermore, also measured river water temperatures were simulated very well with the physical water temperature module of LARSIM (Figure 7, Ishikawa et al. 2021).

Table 4: Results of calibration for four gauges in Passaúna catchment. “Ref” refers to reference values, i.e. for measures of fit the best theoretically possible value, for all other measures the value deduced from measured discharge. “Sim 1“ refers to calibration results based on homogeneous calibration parameters for all four gauges. “Sim 2“ refers to simulation results after separate calibration of each gauge.

		r^2	**NSE**	**NSE_ln**	**balance**	**MNQ**	**MQ**	**MHQ**	**BFI**
unit		[-]	[-]	[-]	[-]	[m³/s]	m³/s	m³/s	-
Montante A. Sanitário	Ref	1.00	1.00	1.00	1.00	0.16	0.35	4.2	0.64
	Sim 1	0.69	0.66	0.70	0.97	0.15	0.34	2.4	0.62
	Sim 2	0.70	0.66	0.77	0.98	0.17	0.35	2.5	0.68
Jusante A. Sanitário	Ref	1.00	1.00	1.00	1.00	0.29	0.55	6.5	0.63
	Sim 1	0.68	0.67	0.65	1.03	0.24	0.57	4.1	0.61
	Sim 2	0.68	0.66	0.72	1.01	0.28	0.55	4.4	0.65
Colonia Dom Pedro	Ref	1.00	1.00	1.00	1.00	0.27	0.67	6.5	0.54
	Sim 1	0.73	0.63	0.51	0.81	0.20	0.53	4.2	0.61
	Sim 2	0.73	0.69	0.68	0.98	0.26	0.64	5.5	0.58
Campo Largo	Ref	1.00	1.00	1.00	1.00	0.67	2.01	16.4	0.56
	Sim 1	0.79	0.75	0.77	0.99	0.73	1.99	15.1	0.57
	Sim 2	0.80	0.77	0.80	1.00	0.76	1.99	15.2	0.58

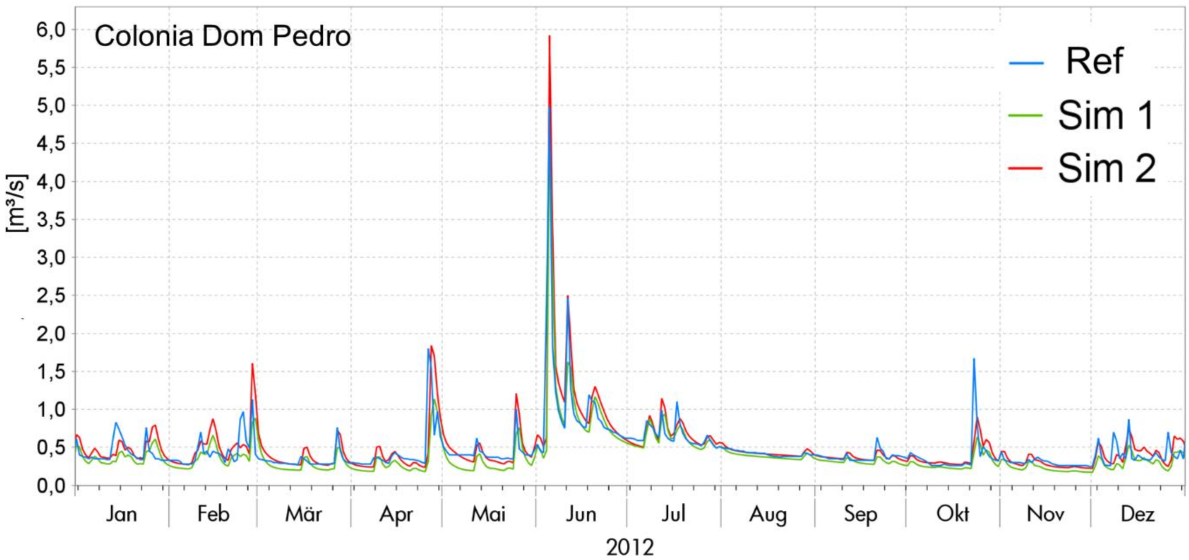


Figure 3. Simulation result for year 2012 at gauge Colonia Dom Pedro / Rio Cachoeirinha (blue: measured discharge, green: simulated discharge based on homogeneous calibration parameters for all four gauges, red: simulated discharge based on separate calibration of each gauge).

5.2.3. Results - Applications of the LARSIM models

Both models were used to supply our project partners with simulation results, including long term river discharges, overall discharges into the reservoirs, water balance of the reservoirs, evapotranspiration within the catchments and evaporation from the reservoirs, spatially distributed runoff components for the different land cover categories and river water temperatures.

In order to demonstrate the potential of water balance modeling in the context of reservoir management, we also applied the Passaúna model to several site-specific problems.

5.2.3.1. Analysis and management of the water balance of the Passaúna reservoir

SANEPAR, the operator of Passaúna reservoir, uses “measured” time series of drinking water abstraction, discharge via the bottom outlet and discharge via the spillway to operate the reservoir. Combining these data with the simulated total inflow into the reservoir, yielded a deficit of the reservoir’s water balance (i.e. discharge from the reservoir was much bigger than inflow into the reservoir). To analyze the reasons for this deficit, we simulated the reservoir within the LARSIM model, by using total simulated inflow into the reservoir (including evaporation from and precipitation to the reservoir surface), a water volume - water level relation derived by KIT IWG-SWW and plausible constant values for drinking water abstraction and discharge via the bottom outlet. Finally, discharge via the spillway was dynamically computed with Poleni’s formula from the continuous simulation of the water level. These simulations showed that discharges via the bottom outlet and via the spillway, as provided by SANEPAR as measured data, were much too high. These findings could meanwhile be corroborated by downstream discharge measurements. Consequently, SANEPAR is presently revising the calculation of discharge via bottom outlet and spillway, which will considerably improve their ability to manage the reservoir adequately in the future.

We used the combined LARSIM model of the catchment and the reservoir to demonstrate the potential of water balance modeling for planning and operating reservoirs. With various scenarios, we showed that it is essential to know the overall inflow into the reservoir, the temporal distribution of inflow throughout the year and extreme (high and low) inflow conditions to operate an existing reservoir or to plan a new one.

Figure 40 demonstrates the outcome of one quite simple scenario for the Passaúna reservoir: Increasing the minimum discharge of the reservoir from 0.5 m^3/s to 1.5 m^3/s would reduce the reservoir minimum volume by approximately 20 mio. m^3 when applying conditions of the year 2017. Furthermore, also the dynamics of discharge downstream of the reservoir would change considerably. Of course, such scenarios can be run with respect to many other questions, such as the maximum viable drinking water extraction rate, the potential effect of climate change on the availability of drinking water, the potential of the reservoir for downstream flood protection and many others.

In comparison to other methods for the assessment of reservoirs, WBM have a high temporal resolution and thereby can easily consider the temporal evolution of storage volume, which is essential to assess for example inter-annual effects. WBM can also provide information for non-observed parts of the catchment and on complex spatial interactions, e.g. the effects of several parallel or sequential reservoirs. Process-oriented water balance models, such as LARSIM, are also capable to predict the impact of changing environmental conditions (e.g. climate change). Once set up, they are thus reliable and versatile tools to assess the effects of changing conditions and potential counteractions. The consideration and comparison of various scenarios is quite simple. In order to communicate these advantages of water balance modeling to the staff of SANEPAR and other operators of drinking water reservoirs, we prepared two technical flyers together with our Brazilian partners SANEPAR and UFPR. These essentials might help SANEPAR (and hopefully others) to improve the future operation of existing reservoirs and the planning of new ones.

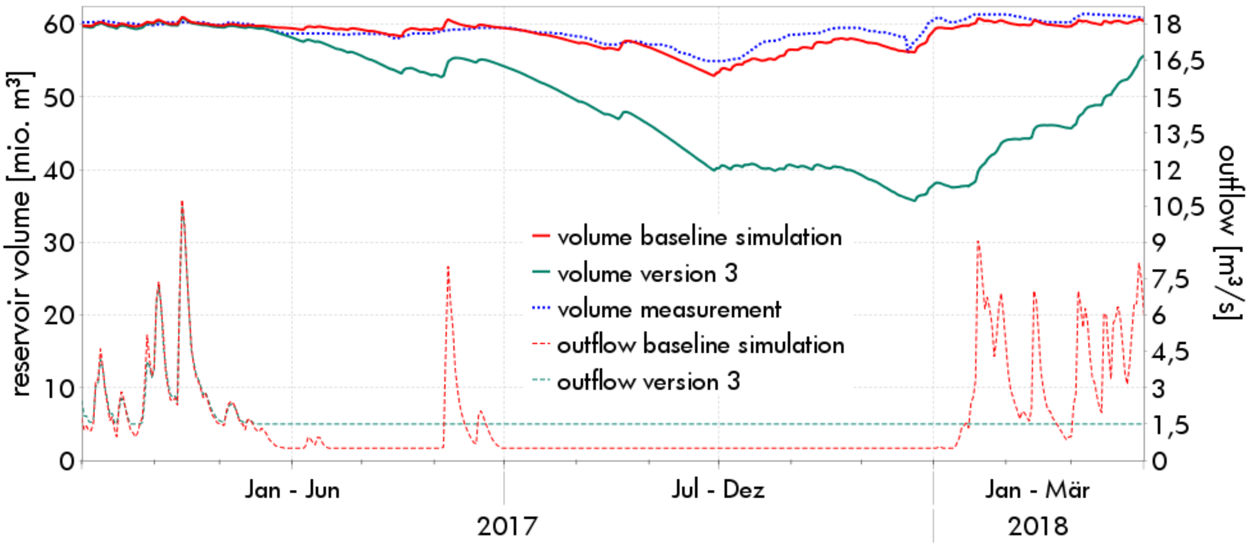


Figure 40: Comparison of two different scenario-simulations of the volume in Passaúna reservoir for the years 2017/2018. The versions differ with respect to minimum outflow. The baseline simulation assumes a min. outflow of 0.5 m³/s, version 3 of 1.5 m³/s (total outflow as broken lines on right y-axis).

5.2.3.2. Land use scenarios for the Passaúna catchment

The Passaúna catchment has experienced significant changes in land use in the past, due to fast urbanization and changes in agricultural activities. Land use changes are in the context of the project mostly relevant with respect to substance inflow into the reservoir. To assess the effects of land use changes on water quality in the Passaúna reservoir, two land use scenarios have been set up and have been simulated with LARSIM to provide scenario input data for the emission modeling with MoRE. The scenarios have been defined in cooperation with KIT IWG SSW as follows:

- Scenario 1: Worst case – Assumption that current land-use dynamics will continue (increased urbanization and sealing (approx. +26% in 15 years), increase of agricultural activities (approx.. +40% in 15 years))
- Scenario 2: Best management – Assumption that urbanization remains at present state and 50% of the cropland will be afforested

Both scenarios were integrated and simulated using LARSIM. The results for total inflow into the reservoir changed only very slightly with respect to the baseline simulation and therefore, they were not used as scenario input for hydrodynamic modeling. However, the land use specific discharge components relevant for emission modeling were analyzed and provided to KIT IWG SSW as input for scenario emission modeling.

Scenario 1 results in more direct runoff from sealed areas as compared to the baseline simulation, whereas groundwater recharge is reduced (Figure 41, center). In scenario 2, discharge components change only very slightly in comparison to the baseline simulation (Figure 41, right). However, when land use specific runoff components, which are relevant for emission modeling, are analyzed, differences between the scenarios and the baseline simulation are more prominent. Figure 42 shows the scenario results for those runoff components, which are most relevant drivers in the emission modeling. Although runoff from sealed areas is most relevant with respect to quantity and absolute changes, also surface runoff from cropland differs significantly in the three simulations. Depending on substance concentration, also less prominent differences in land use specific runoff components can be relevant in emission analysis.

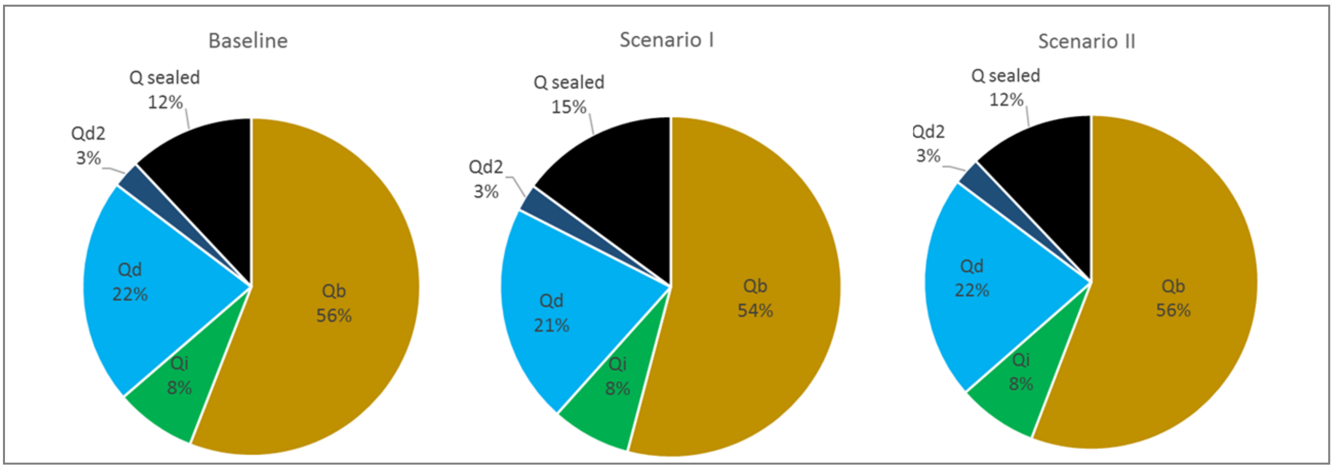


Figure 41: Shares of different runoff components in the baseline simulation and in two land use scenarios (Qb=baseflow, Qi= slow interflow, Qd=fast interflow, Qd2=surface runoff, Qsealed= runoff from sealed areas).

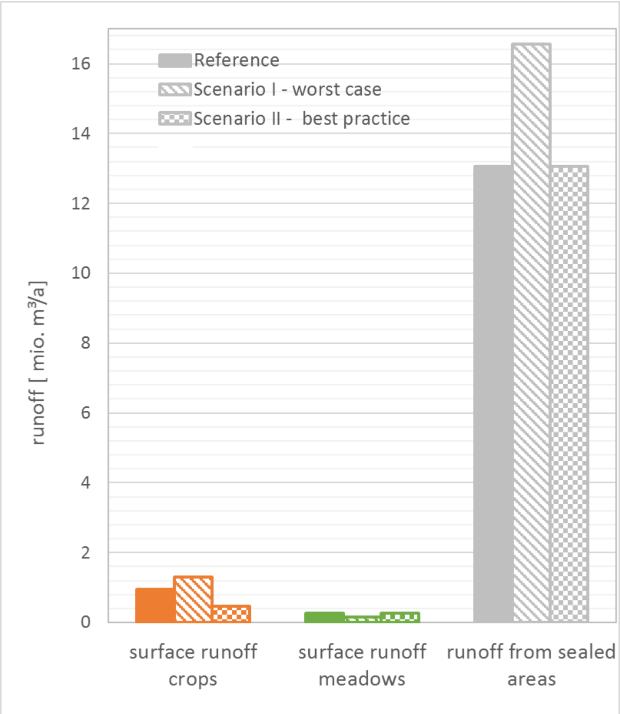


Figure 42: Comparison of relevant land use specific runoff components in the baseline simulation and in two land use scenarios.

5.2.3.3. River water temperatures, stream shading and reservoir water quality

The intrusion depth of water, flowing into a reservoir, is mainly governed by the temperature of the inflowing water and the thermal stratification of the reservoir. The resulting intrusion depth strongly influences the distribution of the nutrient load in the reservoir and its availability for algae growth. Thus, the temperature of inflowing river water may affect eutrophication and water quality of the downstream reservoir. The temperature of inflowing river water is influenced by land use in the catchment, especially through shading by riparian vegetation.

Based on these fundamental relations, we tested the potential influence of riparian shading on inflow characteristics for Passaúna reservoir together with our project partners at the University of Koblenz-Landau (UKL) (WP6). To do so, we performed catchment-scale hydrological and stream temperature modeling for the present state and two scenarios of altered stream shading with the LARSIM water temperature module. Our partners at UKL used the results along with their measurements of reservoir stratification to assess the influence of stream shading on inflow characteristics and potential influences on reservoir water quality. To our knowledge, this is the first study, dealing with the potential effect of stream shading in the catchment on inflow characteristics in a downstream reservoir. The study is described in more detail by Ishikawa et al. (2020; 2021).

To analyze the potential effect of stream shading on river water temperature and inflow dynamics we simulated the present state of stream shading and two scenarios using the water temperature module of LARSIM which is described by Haag and Luce (2008). In the "full shading" scenario we assumed that all river reaches within the catchment are completely shaded by riparian vegetation, which corresponds to a shading factor of 85% for incoming shortwave radiation (Regenauer et al. 2019). In the "no shading" scenario we assumed that riparian vegetation is completely removed, which corresponds to a shading factor of 0% for all river reaches.

The upper panel of figure 7 shows the results of discharge simulations for the present state. As mentioned above and demonstrated by Krumm et al. (2019) simulated discharge is generally in good agreement with measurements (which were only available until September 2018). The lower panel of Figure 43 shows measured and simulated river water temperatures. The simulation for the present state of stream shading closely fits measured stream water temperatures, with a Nash Sutcliffe efficiency of 0.96 and a mean absolute error of 0.47 °C. Linear regression of measured versus simulated water temperatures resulted in a slope of 1.0, an intercept of −0.27 °C and a R^2 of 0.98, indicating that the simulation is not biased and well suited for scenario predictions.

The scenario with full shading results in a moderate reduction of the river water temperature at the reservoir inflow in comparison to the present state (Figure 43). The simulated temperature differences range between −0.1 °C and −2.0 °C with an average of −0.8 °C. The effect of full shading is only modest, because the degree of stream shading in the present state is already quite high. The scenario with no shading results in significantly higher inflow temperatures (Figure 43). Compared to the present state of shading, the increase of daily mean inflow temperatures varied between +0.1°C and +4.7 °C with an average of +2.2°C. This increase is non-linear with higher values in summer, which is due to the higher contribution of shortwave radiation to the overall energy balance during summer. The largest differences occurred in December 2018, when high shortwave radiation and low flow situations coincided. The difference in water temperature for the two contrasting scenarios without shading and with full shading ranged between +0.3 °C and +6.7 °C with an average difference of +3.0 °C. A comparison of our results with the scientific literature shows that the projected influence of riparian shading on river water temperature is realistic (see Ishikawa et al. 2021).

The analysis of UKL showed that the changes of inflow temperatures caused by the no shading scenario would strongly influence the inflow characteristics in the downstream reservoir, promoting a higher likelihood of interflows and even generating overflows. Consequently, no shading of the rivers in the catchment would increase the nutrient load entering the photic zone of the reservoir and thereby contribute to a degradation of reservoir water quality (Ishikawa et al. 2021).

Our study is the first one to show, that stream shading in the catchment can significantly affect reservoir hydrodynamics and potentially water quality. Deforestation in the catchment and the removal of tall vegetation along riparian zones of streams leads to increased river water temperatures, which may cause a degradation of water quality in the downstream reservoir due to changes in reservoir hydrodynamics. Our findings revealed a so-far overlooked mechanism, by which reservoir water quality is affected and may potentially also be managed by altering catchment properties and land use. This important mechanism should be investigated for a broader range of reservoirs and taken into account as a potential tool of long-term reservoir management.

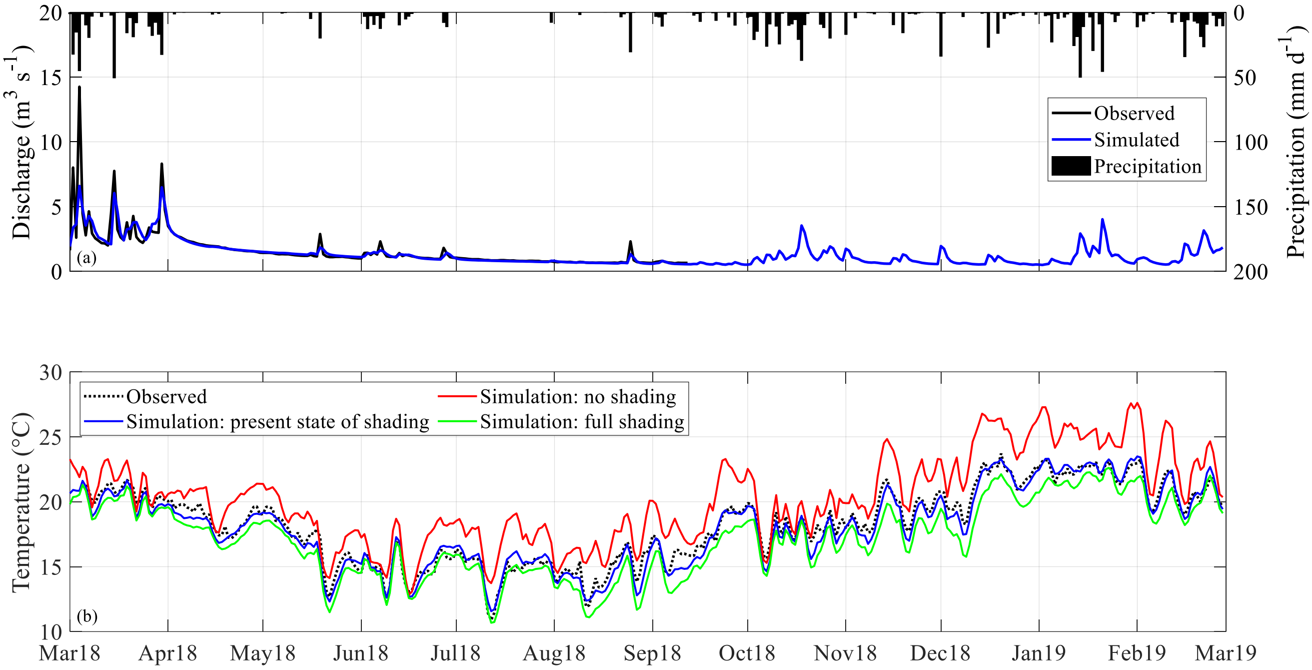


Figure 43: Observed precipitation along with measured and simulated hydrographs of the Passaúna River at gauge Campo Largo (upper panel). Time series of observed and simulated water temperature in the Passaúna River at the gauge (lower panel).

5.2.4. Model simplification and minimum requirements

The LARSIM WBM model for the Große Dhünn can be viewed as state-of-the-art, whereas Passaúna model is much simpler, since its maximum complexity is limited by data availability. With respect to a global model applicability, data availability is the most common limitation for model complexity. Therefore, it is important to know, how model performance and applicability are influenced by a reduction of model complexity. To shed some light on that question, we reduced the complexity and data demand of the Große Dhünn LARSIM model gradually and evaluated model performance with respect to 1) discharge at the gauges, 2) water balance of the downstream reservoir and 3) spatial heterogeneity of runoff generation.

We simulated nine versions of the LARSIM WBM of Große Dhünn, which differ in model complexity and data demand (table 3). Note that version 8 is equivalent with the model version used for the Passaúna model.

5.2.4.1. Modeling discharge at gauges

We evaluated the performance at gauges with common metrics, such as Pearson's R^2 and the Nash Sutcliffe efficiency (NSE), but also by the Volume efficiency (VE) (Criss & Winston 2008) and a modified non-parametric form of the Kling Gupta efficiency (KGE) (Pool et al. 2018). Moreover, we also introduced a new metric, which is similar to NSE, but uses the results of the reference model as a benchmark (NSEbenchmark). Hence, positive or negative values of NSE-benchmark indicate, that the model version under investigation performs better or worse than the reference model. The results are summarized in Table 6.

Table 5: LARSIM WBM versions for the Große Dhünn catchment.

No.	Description of model version	globally available data	reduced spatial resolution of model parametrization	reduced spatial distribution of forcing meteorological data	reduced temporal resolution	reduced data demand for meteorological forcing
1	State-of-the-art model in hourly timestep (reference model)					
2	Land cover and evaporation parameters derived from globally available remote sensing data by EFTAS (as for Passaúna)	x				
3	No spatial distribution of soil data (as for Passaúna)		x			
4	Using only one station for precipitation			x		
5	Using only one station for all other meteorological parameters except precipitation			x		
6	Daily instead of hourly timestep				x	
7	Daily timestep with simplified simulation of evapotranspiration				x	x
8	Typical simplified model: combination of 2, 3 and 6 (equals model for Passaúna)	x	x		x	
9	Daily timestep with globally available meteorological data (climate model)	x		x	x	x

Table 6: Performance of the LARSIM WBM versions for the Große Dhünn at discharge gauges Neumühle and Unterpilghausen.

	Gage Neumühle						Gage Unterpilghausen					
No.	R^2 [-]	NSE [-]	NSE ln(Q) [-]	VE [-]	KGE non-par. [-]	NSE bench mark	R^2 [-]	NSE [-]	NSE ln(Q) [-]	VE [-]	KGE non-par.. [-]	NSE bench mark
1	0.86	0.86	0.82	0.71	0.89		0.85	0.85	0.79	0.68	0.86	
2	0.86	0.85	0.83	0.71	0.90	+0.01	0.85	0.85	0.80	0.69	0.87	+0.02
3	0.85	0.85	0.83	0.71	0.90	-0.01	0.85	0.84	0.78	0.68	0.87	-0.00
4	0.78	0.78	0.77	0.66	0.86	-0.18	0.80	0.80	0.74	0.64	0.83	-0.13
5	0.87	0.87	0.82	0.71	0.90	-0.00	0.84	0.84	0.78	0.68	0.86	-0.01
6	0.86	0.86	0.83	0.72	0.90	-0.02	0.84	0.84	0.79	0.69	0.87	-0.03
7	0.85	0.85	0.80	0.71	0.88	-0.06	0.84	0.84	0.75	0.68	0.84	-0.08
8	0.85	0.85	0.83	0.71	0.90	-0.04	0.84	0.84	0.79	0.69	0.87	-0.03
9	0.74	0.73	0.65	0.61	0.79	-0.42	0.74	0.73	0.62	0.58	0.76	-0.40

With respect to discharge at the gauges, version 2 performs as well or even slightly better than the reference model no. 1. Thus, deriving land cover data from remote sensing does not influence the ability of the LARSM WBM to simulate discharge at the gauges adequately. Similarly, also using uniform soil data without spatial distribution (version 3) does not decrease performance with respect to discharge at the gauges. In contrast, using only one single input for precipitation (version 4), without considering spatial variability of precipitation reduces model performance significantly, even though we consider relatively small catchments. Using only one station for all other meteorological parameters (version 5), on the other hand, does not influence model performance negatively.

Also increasing the time step from hourly to daily (version 6), only has minor effects on model performance at the river gauges. However, one has to keep in mind, that it is generally not possible to capture dynamic discharge events accurately in small catchments with a time step of one day. This means, the model performs well with respect to mean daily discharge, but it can of course not capture short-term peak discharges, which might be relevant for many tasks.

LARSIM usually simulates evapotranspiration with the Penman-Montheith approach, which needs five meteorological input parameters. It is also possible to simplify the simulation of evapotranspiration, using the approach of Oudin et al. (2005). This simplified approach only needs the air temperature as meteorological input, which is much more widely available than other meteorological parameters. Thus, simplifying evapotranspiration (version 7) also reduces data demand. The simplified approach to evapotranspiration reduces model performance at the gauges moderately. Nevertheless, version 7 is a feasible approach, if not all meteorological parameters for the Penman-Monteith approach are available.

Version 8, which represents the model version used for Passaúna, performs almost as well as the reference model. In conclusion, the Passaúna model version seems to be adequate to simulate river discharges at gauges.

Finally, we used a simplified model and forced it with globally available meteorological data of the ERA5-Land climate model (version 9). This version performed considerably worse. However, even with version 9 we could still achieve NSE values of 0.73, which is still satisfactory for small catchments of 11 and 21 km^2.

5.2.4.2. Small scale spatial heterogeneity

Since the results for the water balance of the downstream reservoir are similar to those at the gauges, this aspect is not discussed here. In contrast, the evaluation with respect to spatial heterogeneity of runoff generation showed a completely different picture. We do not have a reference value for spatial heterogeneity of runoff generation. Therefore, we had to compare the spatial variability of runoff generation and evaporation created by the Hydrological Response Units (HRU) of the different model versions using the spatial coefficient of variation (CV) (Figure 44).

The results show, that evapotranspiration of all model versions varies much less in space than runoff generation. Nonetheless, simplifying the simulation of evapotranspiration (versions 7 and 9) also reduces the spatial variability of evapotranspiration. Total runoff and all four runoff components show the largest variability for the most complex model version 1 (the state-of-the-art reference model). It is likely that even the reference model still underestimates the real spatial variability of runoff generation. Hence, lower CV-values may be interpreted as a worse performance. Consequently, all model simplifications tend to lower performance than the reference model.

In general, the simplest model versions 8 and 9 exhibit the lowest variability for total runoff, base flow (groundwater recharge) and surface runoff. Using spatially homogeneous soil data (versions 3 and 8) particularly reduces the spatial variability of base flow generation. This is due to the fact, that groundwater recharge strongly depends on (spatially variable) soil hydraulic properties. Only using one precipitation station (version 4) also reduces the spatial variability of total runoff, surface runoff and interflow. Changing the time step from hourly to daily (version 6) reduces the spatial variability only moderately. Finally, the spatial variability of runoff generation seems to be almost the same when using land cover derived from remote sensing (version 2) instead of using ATKIS land cover.

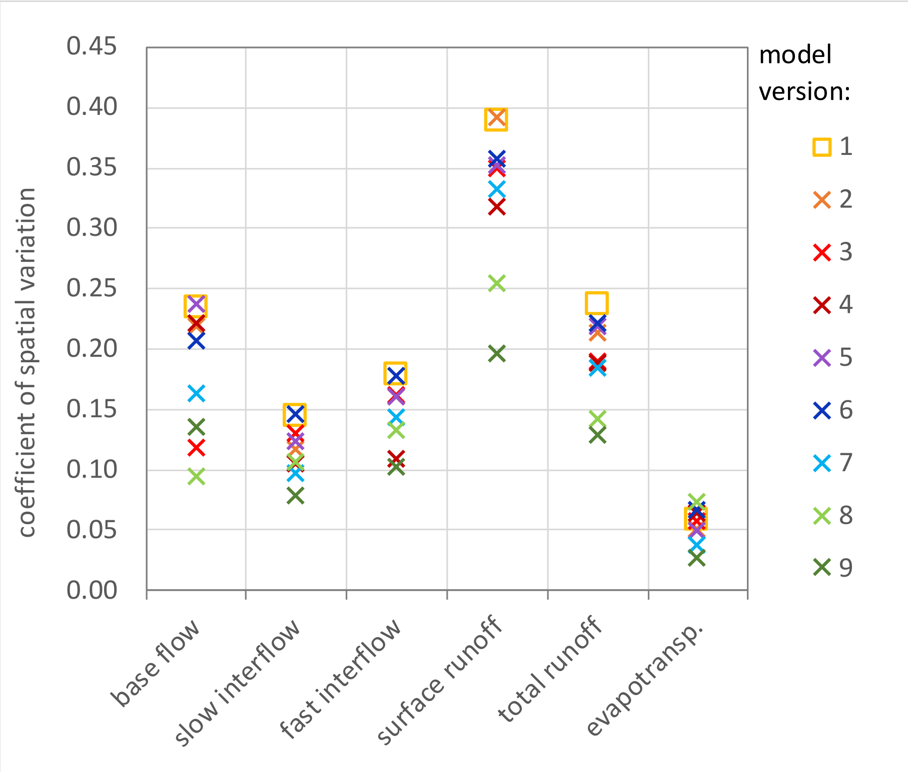


Figure 44: Coefficient of spatial variation for runoff generation and evapotranspiration for the HRU of the different LARSIM versions of Goße Dhünn.

Obviously, the spatial variability of runoff generation is very sensitive to model simplifications. Using land cover data derived from remote sensing instead of ATKIS and increasing the time step from hourly to daily are the only simplifications that only show minor effects on spatial variability of runoff generation. All other simplifications reduce the spatial variability of runoff generation significantly.

5.2.4.3. Model requirements and limitations

Our findings highlight, that simplified model versions of LARSIM (such as the model for Passaúna) with moderate data demand are well suited to simulate the discharge at river gauges. Even with globally available meteorological data, one can still achieve satisfactory results for gauges. Hence, simplified (LARSIM) models, which are based on land cover classifications, derived from globally available remote sensing data, reasonable assumptions for soil parameters and globally available meteorological data may be used to simulate the discharge at gauging stations (also see Krumm et al. 2019). It is thus possible to setup such a simplified LARSIM model almost anywhere in the world.

However, these simplified models heavily depend on gauge specific calibration. The specific hydrological response of different (gauged) catchments is reproduced by fitting spatially lumped parameters to measured discharges. These simplified models do not represent the spatial heterogeneity of the hydrological processes within the catchments, which is indicated by a reduced spatial variability of runoff generation. Thus, one has to be careful, when using simplified models for tasks, which rely on spatially distributed hydrological results. In addition, if gauge specific calibration influences results significantly, tasks, which rely on extrapolation of model results, have to be considered cautiously.

To account for spatial variability of hydrological response within the catchments, land cover information from remote sensing is important, but one also needs spatially distributed information of soil hydraulic properties (e.g. soil maps with physical parameters). Such maps are readily available in Germany and many parts of Europe, but they are not available for many other parts of the world. Therefore, the lack of adequate soil physical maps is one major obstacle to setup LARSIM models, which also adequately account for hydrological heterogeneity on a small scale within catchments, anywhere in the world.

5.2.5. Summary and conclusions

We successfully set up LARSIM water balance models for the catchments of the drinking water reservoirs Große Dhünn (Germany) and Passaúna (Brazil). In the case of Passaúna we supplemented the water balance model with the physically based water temperature module of LARSIM. We performed various model runs and provided the necessary simulation results to our project partners, including discharge, river water temperature, evapotranspiration and spatially distributed runoff generation for different land use classes. We applied the Passaúna LARSIM model:

- to demonstrate the potential of water balance modeling for planning, operating and managing (drinking water) reservoirs
- to resolve problems with the “measured” water balance of the Passaúna reservoir
- to quantify the effect of possible land use changes in the catchment on discharge, on runoff generation and potentially on diffuse nutrient emissions
- to demonstrate the potential effect of stream shading within the catchment on water quality in the reservoir

For these tasks, we collaborated with different German and Brazilian partners. We presented our findings and tools at the project workshops and discussed them with the Brazilian partners (mainly SANEPAR and UFPR).

We successfully developed tools to modify existing LARSIM models and to assess the performance of different model versions in a comparative way. We simplified the state-of-the-art model for the Große Dhünn gradually and assessed the performance with respect to 1) discharge simulation at gauges and 2) representing spatial variability of the hydrological response. Discharge at gauges can be simulated satisfactorily with a relatively simple model version, which can be set up and run with globally available data. However, representing spatial heterogeneity of runoff generation on a small scale, within the catchments requires a more complex and data demanding model version. The major limitation for setting up such a model version anywhere in the world is the availability of maps (geo-data) with adequate soil hydraulic parameters.

References of WP2:

Criss, R. E., Winston, W. E. 2008. Do Nash values have value? Discussion and alternate proposals. Hydrological Processes. 2008, 22, S. 2723-2725.

Haag, I. (2018): Regionalisierung und Simulation der Wassertemperatur – Ergebnisse und Bewertungen. In: AK KLIWA (Hrsg.): 6. KLIWA-Symposium 22.-23.05.2017 in Baden-Baden, Fachvorträge. KLIWA-Berichte, S. 120-132. https://www.kliwa.de/_download/KLIWAHeft22.pdf

Haag, I., Aigner, D., Krumm, J., Regenauer, J., Steinbrich, A., Weiler, M., Sieber, A., Bremicker, M. (2019): Simulation von Hochwassern in der Folge von Starkregen mit LARSIM - ein Beispiel für die zielführende Nutzung vorhandener Bodendaten. Forum für Hydrologie und Wasserbewirtschaftung, 41.19, S. 105-110. https://www.fghw.de/publikationen

Haag, I., Krumm, J., Aigner, DSteinbrich, A., Weiler, M., Bremicker, M. (2021): Simulation von starkregenbedingtem Hochwasser mit dem Wasserhaushaltsmodell LARSIM. (in Vorbereitung)

Haag, I., Luce, A. (2008): LARSIM-WT: an integrated water-balance and heat-balance model to simulate and predict stream water temperatures. Hydrological Processes 22, 1046-1056.

Ishikawa, M., Haag, I., Krumm, J., Teltscher, K., Lorke, A. (2020): The effect of stream shading on inflow characteristics in downstream reservoirs. Workshop on Physical Processes in Natural Waters, 15-19 June, 2020, Leipzig. https://www.ufz.de/index.php?de=47282

Ishikawa, M., Haag, I., Krumm, J., Teltscher, K., Lorke, A. (2021): The effect of stream shading on inflow characteristics in downstream reservoirs River research applications (under review)

Krumm, J., Haag, I. (2019): Multikriterielle Analyse eines Wasserhaushaltsmodells unter Berücksichtigung der Unsicherheit der Datengrundlage. Forum für Hydrologie und Wasserbewirtschaftung, 41.19, S. 111-116. https://www.fghw.de/publikationen

Krumm, J., Haag, I., Wolf, N. (2019): Adaption des Wasserhaushaltsmodells LARSIM zur Anwendung bei veränderter Datenlage und unter subtropischen Bedingungen am Beispiel des Passaúna (Brasilien). Forum für Hydrologie und Wasserbewirtschaftung, 41.19, S. 117-122. https://www.fghw.de/publikationen

LEG – LARSIM Entwicklergemeinschaft (2020): Das Wasserhaushaltsmodell LARSIM – Modellgrundlagen und Anwendungsbeispiele. http://www.larsim.info/dokumentation/LARSIM-Dokumentation.pdf, Stand: 05.03.2020

LUBW – Landesanstalt für Umwelt Baden-Württemberg (2017): Fortschreibung der WHM Oberrhein, Hochrhein und Bodensee mit aktualisierten Bodendaten und landesweite LARSIM-Ausgaben für METRIS (Monatswerte für 1998-2014). HYDRON GmbH on behalf of Landesanstalt für Umwelt Baden-Württemberg (internal report).

Oudin, L., Hervieu, F., Michel, C., Perrin, C., Andréassian, V., Anctil, F. and Loumagne, C. (2005): Which potential evapotranspiration input for a rainfall-runoff model? Part 2 - Towards a simple and efficient PE model for rainfall-runoff modeling. - Journal of Hydrology 303(1-4), 290-306.

Pool, S., Vis, M., Seibert J. (2018): Evaluating model performance:towards a non-parametric variant of the Kling-Gupta efficiency, Hydrological Sciences Journal, DOI: 10.1080/02626667.2018.1552002

Regenauer, J., Haag, I., and Aigner, D.: 2-Grad-Ziel für unsere Bäche – Wassertemperatur und Beschattung, Intermediate Report on behalf of the Environmental Agencies of the federal States of Bavaria, Baden-Württemberg, Hesse and Rhineland-Palatine, 2019.

Steinbrich, A., Leistert, H.& Weiler, M. (2016): Model-based quantification of runoff generation processes at high spatial and temporal resolution. Environ. Earth Sci. (2016)75, 1423 DOI 10.1007/s12665-016-6234-9.

5.2.6. Flyers

MuDak-WRM

FONA Research for Sustainable Development BMBF — Sponsored by the Federal Ministry of Education and Research

LARSIM water balance model for the Passaúna catchment and reservoir

Context

The water balance of a catchment is one of the most relevant factors in the management of reservoirs. Water balance models can deliver valuable information on all components of the water balance of the reservoir and can thereby contribute to sustainable reservoir management.

Water balance model LARSIM

LARSIM simulates the terrestrial water balance of catchments spatially distributed and temporally continuously in a process-oriented way. Its setup for a given catchment is based on data on the river network, topology, soil hydraulic properties and land use. Forcing data for the model consist of meteorological data, most notably precipitation. The most common data basis for calibration and validation is measured discharge at gauges.

Outputs of LARSIM

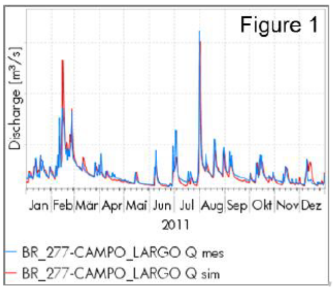
Water balance models deliver results for different parameters on various spatial and temporal scales. The minimum spatial and temporal scale depends on the resolution of input data.

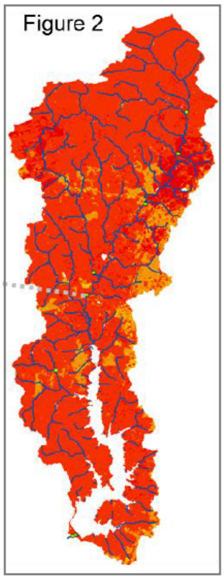
The most obvious output is simulated discharge along the represented river network, e.g. at hydrological gauges (Figure 1), but also at other points of interest (e.g. ungauged inflows into the reservoir). In LARSIM, this often-used outcome is based on spatially distributed computation of discharge generation. Therefore, it is also possible to obtain spatially distributed results on runoff. This kind of result is also available for other components of the water balance, e.g. evapotranspiration (Figure 2). Both kind of results can additionally be differentiated by their flow paths into different runoff components, such as groundwater recharge or surface runoff (Figure 3). For some parameters, even further differentiation is possible, e.g. spatially distributed runoff components differentiated by the underlying land use (e.g. surface runoff from sealed areas or agricultural land).

The model can also simulate the temporal evolution of water level and water volume in the reservoir, which is essential for the assessment of the availability of drinking water and different management scenarios.

This type of results for Passaúna reservoir is in more detail presented on the extra flyer "*Using hydrological models to plan and manage reservoirs with respect to water quantity*".

Moreover, the LARSIM model for the Passaúna catchment simulates water temperature. Therefore, it is possible to obtain water temperature results along the river network at points of interest (not for standing water bodies; Figure 4 and 5).





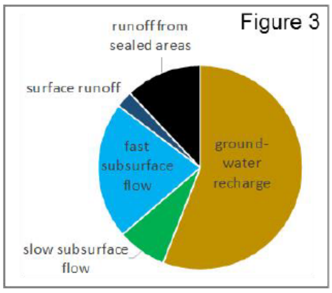


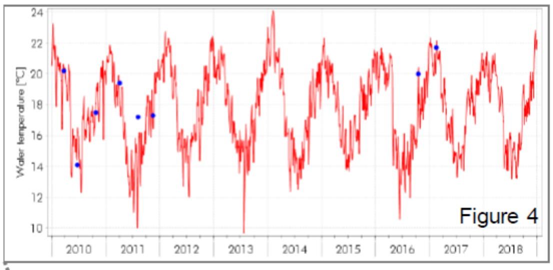
Figure 1: Comparison of simulated (red) and measured (blue) daily discharge time series [m³/s] at gauge BR277/Passaúna.

Figure 2: Simulated spatial distribution of average annual evapotranspiration [mm/a] for the catchment of Passaúna reservoir.

Legend Figure 2
evapotranspiration [mm/a]

water	501 - 750
< 250	751 - 1000
251 - 500	1001 - 1100

Figure 3: Simulated long-term percentage shares of different runoff components for Passaúna catchment.



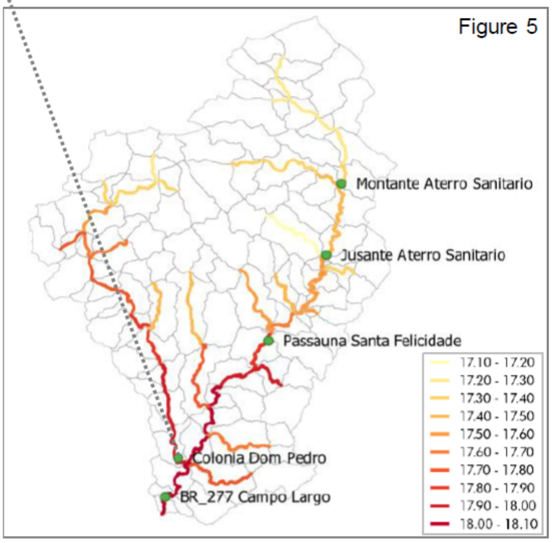


Figure 4: Comparison of simulated (red) and measured (blue) daily water temperature at station Colonia Dom Pedro/Rio Cachoeirinha.

Figure 5: Spatial distribution of simulated average annual water temperature [°C] for the Passaúna river network.

Applications of water balance models

As water balance models run temporally continuously and spatially differentiated, they can supplement information on parameters, which are difficult, laborious or expensive to measure. Once a model has been setup and calibrated, it can be run for all periods, for which meteorological forcing data is available.

Therefore, the models allow not only the simulation of forecasts (such as for flood warning), but also the assessment of effects of hypothetical changes in the catchment (e.g. land use alterations or climate change) on the hydrology.

Applications within MuDak-WRM

Within MuDak-WRM the LARSIM water balance model set up for the Passaúna catchment serves two primary goals: Spatially differentiated, land use specific runoff components are used as input for the emission model MoRE. Discharge and water temperature results for all inflows (including not monitored inflows) to the reservoir are used as boundary conditions for the hydraulic and water quality modelling of the reservoir itself. Furthermore, the model has been applied to check the available information on the water balance of the reservoir (inflows, outflows, drinking water intake and water level variations) for consistency.

Potential future applications

The existing model can be used for all further purposes, for which the necessary driving data is available. This includes the calculation of scenarios (e.g. climate change or land use scenarios). Impacts on both discharge and water temperature in the rivers can be assessed under scenario conditions. Also, the impact of such scenarios (and operation scenarios) on the water volume in the reservoir and the availability of drinking water can be assessed (see example results for Passaúna reservoir on the extra flyer "*Using hydrological models to plan and manage reservoirs with respect to water quantity*"). If coupled with MoRE, the model results also allow drawing conclusions on the water quality in the reservoir. Thus, the model cannot only help to understand the present water balance, water temperature and water quality conditions, but can also help supporting decisions, which might influence future conditions.

Authors Krumm, J.; Haag, I.; HYDRON GmbH
Contact julia.krumm@hydron-gmbh.de
Funded by Federal Ministry of Education and Research, BMBF
Web www.mudak-wrm.kit.edu

MuDak-WRM

FONA Research for Sustainable Development BMBF

SPONSORED BY THE Federal Ministry of Education and Research

Using hydrological models to plan and manage reservoirs with respect to water quantity

Context

In order to plan new reservoirs or to manage existing reservoirs, it is essential to know:

- overall inflow into the reservoir
- temporal distribution of inflow throughout the year
- extreme inflow conditions

Hydrological models can provide this information. Therefore, their application can be helpful at different stages of reservoir management:

- planning of new reservoirs
- long-term management of existing reservoirs
- operational short-term management of existing reservoirs

Planning new reservoirs

Water balance models provide potential inflow into a planned reservoir. Along with the planned reservoir volume and the withdrawal, this is the basis for sound planning of new reservoirs. In addition, extreme conditions (flood and drought inflows) can be evaluated. In this way, it is for example possible to compare potential locations for a new reservoir, assess the availability of drinking water from the reservoir or optimize its volume. To illustrate the planning process, Figures 1 and 2 show time series of Passaúna reservoir water volume resulting from simulations with varied drinking water abstraction and varied minimum ecological outflow.

Long-term management of reservoirs

Similar to the application of water balance models in the planning of new reservoirs, they can also be applied in the long-term management of existing reservoirs. Their application allows the assessment of potential changes in the long-term operation of the reservoir, e.g. increased drinking water abstraction (Figure 1), higher ecological minimum discharge (Figure 2) or changes in reservoir volume from silting or modification of the dam. Furthermore, the potential impact of changes in the catchment (e.g. climate change effects, land use changes) can be assessed. To illustrate this, Figure 3 contains example results for time series of Passaúna reservoir water volume with modified precipitation input, which might be regarded as an example for the effects of very dry climatic conditions.

Operational short-term management of reservoirs

Water balance models can also be applied in the operational short-term management of existing reservoirs. To do so, forecasts of meteorological data are needed. In this way, the short-term operation of reservoirs can be optimized based on the actual initial conditions and expected weather conditions. For example, operational forecasting may be used to optimize drinking water abstraction during drought periods or to improve flood retention under wet conditions.

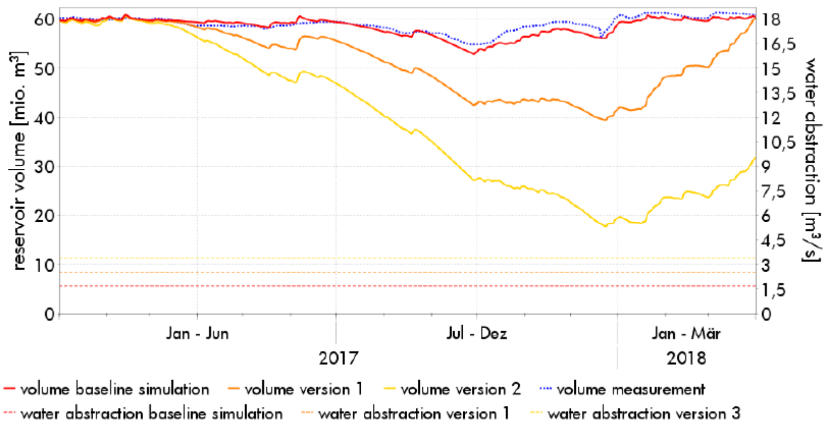


Figure 1: Comparison of three different simulations of the volume in Passaúna reservoir for the years 2017/2018 (solid lines, left y-axis). The versions differ only with respect to drinking water abstraction (broken lines, right y-axis). The baseline simulation assumes an abstraction of 1.7 m³/s, version 1 of 2.55 m³/s (+50%) and version 2 of 3.4 m³/s (+100%).

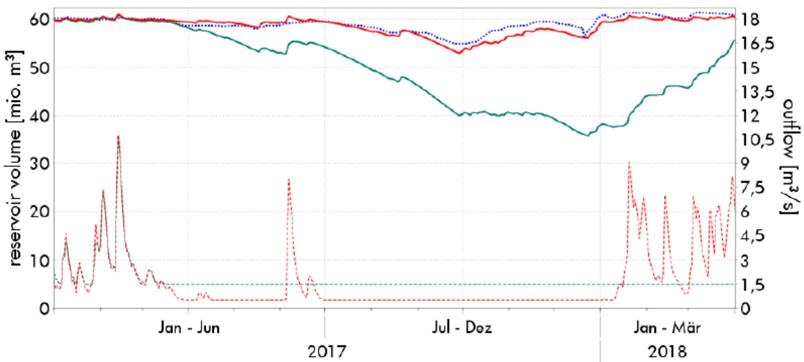


Figure 2: Comparison of two different simulations of the volume in Passaúna reservoir for the years 2017/2018. The versions differ with respect to minimum (ecological) outflow. The baseline simulation assumes a min. outflow of 0.5 m³/s, version 3 of 1.5 m³/s (total outflow as broken lines on right y-axis).

- volume baseline simulation
- volume version 3
- volume measurement
- outflow baseline simulation
- outflow version 3

Potential results

For all three types of application, water balance models can provide the following relevant results:

- inflow into the reservoir
- water volume in the reservoir
- water level in the reservoir (if volume/level relation is known)
- discharge downstream of the reservoir

All results can be provided in high temporal resolution. Therefore, the results are not only valuable with respect to water quantity, but also to deduce information for the assessment of water quality, e.g.:

- number of days during which the water level decreases below a critical value
- (mean) residence time
- number of days with critical (matter) inflow

Advantages of the application of water balance models for reservoirs

In comparison to other methods for the assessment of reservoirs, water balance models have a high temporal resolution and thereby can easily consider temporal evolution e.g. of storage volume, which is essential to assess for example inter-annual effects. They can also provide information for non-observed parts of the catchment and on complex spatial interaction, e.g. the effects of several parallel or sequential reservoirs. Physically-based water balance models, such as LARSIM, are also capable to predict the impact of changing environmental conditions (e.g. climate change). Once set up, they are thus reliable and versatile tools to assess the effects of changing conditions and potential counteractions. The consideration and comparison of various scenarios is quite simple.

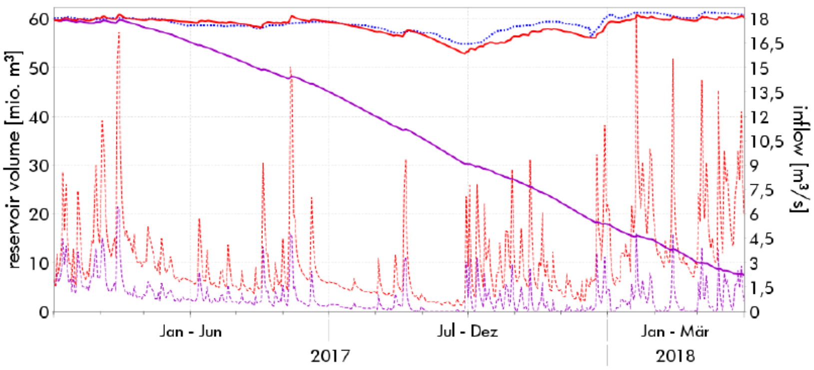


Figure 3: Comparison of two different simulations of the volume in Passaúna reservoir for the years 2017/2018. The versions differ only with respect to precipitation input (broken lines, right y-axis). In version 4, actual precipitation is reduced by 50%.

- volume baseline simulation
- volume version 4
- volume measurement
- inflow baseline simulation
- inflow version 4

Authors Krumm, J.; Haag, I.; HYDRON GmbH
Contact julia.krumm@hydron-gmbh.de
Funded by Federal Ministry of Education and Research, BMBF
Web www.mudak-wrm.kit.edu

5.3. Work package 3 – Hydrodynamics and sediment transport modeling

One possible software for fine sediment and water quality modeling is the commercial hydrodynamic model Delft3D (open source software), which has been successfully used for hydrodynamic problems by the Brazilian partner at UFPR for many years. Delft3D was developed by Deltares, Delft Hydraulics, Netherlands and is a 3D/2D software for modeling hydraulics, sediment transport, solute transport, waves, ecology, and water quality (Delft Hydraulics, 2014). Delft3D contains computational algorithms for simulating the main hydrodynamic processes in the reservoir (e.g., density flow, wind influence on turbulence intensity in the water body) as well as approaches for modeling the cohesive fine sediment processes. For flocculation modeling, for example, a simplifying approach is implemented that considers the influence of salinity on the degree of flocculation and thus on the sinking velocity. However, approaches regarding explicit and direct flocculation modeling (e.g., modeling of turbulence-induced aggregation and disaggregation processes of fine sediment aggregates) have not yet been implemented in Delft3D. Furthermore, the modeling of water quality parameters is possible ("D-Water Quality Module"). The water quality model allows the simulation of biological and chemical transport processes (e.g. organic substances and nutrients like nitrogen and phosphorus as well as more complex organic compounds) for a variety of input model substances.

5.3.1. Introduction and objectives

Reservoirs are used worldwide as water supply source, for hydropower generation and for the control of flood events. In regions with highly variable hydrological regimes they are essential for a sustainable water supply for the community, where storing water for dry periods is necessary and requires a large volume for this aim (Annandale, Morris, & Karki, 2016). In many countries the main source of energy is the hydropower generation e.g. in Brazil 70.1% of the produced energy (Ministerio de Minas e Energia, 2013) and approximately 56% of the municipalities use superficial waters sources for consume (Galli & Abe, 2010).

Ensuring the water quantity and quality of storages reservoirs is the most important management goal to be achieved by public water companies. Water quality parameters can be measured in any temporal resolution, as high as needed. If anomalies are detected in the measurements and they represent a risk for the human consume, immediate action must be taken. In the case that those actions do not produce a rapid impact on the reservoir water quality, it can happen that the supply of the community must be interrupted for long time periods.

Another process taking place in lakes and reservoirs is the density stratification. Vertical stratification affects negatively the quality of water in reservoirs and lakes. There is a decrease in vertical transfer of nutrients between the surface and deep layers, resulting in a light-abundant but nutrient-poor epilimnion and a light-poor but nutrient-rich hypolimnion (MacIntyre, Flynn, Jellison, & Romero, 1999).

A second aspect affecting both the water quality and quantity in reservoirs is the transport and deposition of sediments (see Flyer “3D-numerical modelling of suspended sediment transport in the Passaúna reservoir”; Figure 1). The impoundment of water through the construction of dam reduces dramatically the flow velocities governing the once free flowing river. Those flow conditions allow sediment particles to deposit between the inflow and the dam of the reservoir. If no measures are taken, at some point the sediment will fill up the reservoir, occupying the space that had been planned for water storage and on this way affecting the capacity of providing enough water supply or flood control. It is widely agreed that between 1 to 2% of the world storage capacity of the reservoirs is lost each year (Schleiss, De Cesare, Franca, & Pfister, 2014).

Sedimentation may also influence the water quality of a reservoir by the input of pollutants often attached to the sediment. Fine sediments have the capacity to absorb other substances as a consequence of their high specific surface area. For instance, the fine sediments at the Upper Rhine River in Germany are heavy loaded with the substance hexachlorobenzene (Klassen, 2017) , which is a persistent organic pollutant that may cause some types of cancer. Also, heavy metals and nutrients can be attached to the fine sediments. Due to this fact, the sediment particles can be considered as a source of pollution for water bodies (Taveira-Pinto, Lameiro, Moreira, Carvalho, & Figueuredo, 2014).

In the presented examples, the need for an instrument that helps to plan management strategies for the operation of reservoirs can be clearly seen. A hydrodynamic morphological numerical model (see Flyer “3D-numerical modelling of suspended sediment transport in the Passaúna reservoir”; Figure 2) can serve as a tool for this issue. The use of numerical models for the prediction and study of the processes that take place in water bodies is an established practice. The appropriate modelling of the hydrodynamics of a reservoir includes the simulation of its thermal structure, flow velocities, water residence time and density stratification (Chanudet, 2012). In this order of ideas, it is necessary to build and calibrate the hydrodynamical model before it can be started with the investigations regarding further water quality parameters. It is important to keep in mind that the water temperature is a quality parameter as well.

The behavior of numerical models simulating the hydrodynamics of reservoirs has been widely investigated. Zhang et al (2020) investigated the impact of rainfall, river inflow and wind on temperature stratification in the Tarago Reservoir in Australia using the software DHI MIKE 3. Polli & Bleninger (2019) studied the thermal structure and the density currents present in the Vossoroca reservoir in Brazil using both a 3D and a 1D model. Chanudet, V. et al (2012) set up and calibrated a 3D model of the Nam Theun 2 Reservoir in Lao using the software Delft 3D. 2003 Ahlfeld et al used the software CE-QUAL 2 to study the impact of the water column stratification on the interflow travel time through a laterally averaged 2D model.

Sedimentation in storage reservoir has also been widely simulated, since this is an important issue affecting the life span of these water bodies. Zhang & Wu (2019) analysed the high suspended solid concentrations (SSC) interfiring with the water quality at the withdrawal location in the Deze Reservoir in China using a 3D model. 2017 Hillebrand , Klassen, & Olsen published their studies regarding the deposition of sediments at the run of river reservoir Iffezheim at the Rhine river in Germany. They employed the three dimensional software SSIIM3D. Omer, et al (2015) simulated the hydrodynamics and the sedimentation at the Roseires Reservoir in Sudan using Delft3D in order to optimize future field campaigns for the sediment core extractions of the bottom of the water body. Haun, Kjærås, Løvfall, & Olsen (2013) built and calibrated a 3D model to compute SSC and sediment deposition patterns at the Angostura Reservoir in Costa Rica.

Objectives:

The set up and calibration of numerical models require a high quantity of input data - in the highest possible resolution they can be obtained. The complexity and the amount of data required are rarely measured in regular campaigns or monitoring stations. The demand for data usually leads to the implementation of comprehensive measurement campaigns, which translates into personnel costs and time. In this vein, the main scientific objective of the performed studies can be summarized as follows:

- Determination of the minimal complexity degree of the numerical model in order to still adequately represent the processes taking place in the water body.

The pursuing of the main objective leads to the formulation of the following specific objectives:

- Determination of the crucial processes and related input data sets governing the hydrodynamics and sedimentation in reservoirs.
- Investigation of the lowest data resolution that still allow a good representation of the hydrodynamics and sedimentation.
- Study of different model dimensionalities (3D, 2D, 1D and 0D).

The main and specific objectives coincide with the general and the scientific aims stated in the project proposal.

5.3.2. Preparation and method

In order to set up the necessary numerical models the software Delft3D developed by Deltares (Deltares, 2014) was used. The hydrodynamic/morphological module of Delft3D called FLOW solves the three-dimensional RANS (Reynolds Averaged Navier-Stokes Equations) under the assumption of shallow water conditions, i.e. a hydrostatic pressure distribution is adopted. Delft3D has been applied to simulate the hydrodynamics and sediment transport of many reservoirs, lakes, rivers and estuaries around the world. In a first step a numerical model for the Big Predam of the Dhünntalsperre was constructed and the hydrodynamics and sediment transport were investigated. The results of these analyses are summarized in the partial report for the year 2018 (Zwischenbericht 2018 –KIT AP 3). Those activities served as test phase and instroduction to Delft3D and to have the first impressions about the correlations between the several input data and the quality or variations of the results. For a detailed explanation of the investigation on this reservoir see (Jakobs, 2018). The following methods refere to the studies performed in the Passaúna reservoir in Brazil.

Aiming to achieve the objectives stated in the previous section a complex (as possible) three-dimensional numerical model was set up and calibrated. The main simulation, also called reference case or high resolution simulation, was fed with the highest quality data available for the Passaúna reservoir. The recollection of those data was carried out during the first phase of the activities of the present work package, based on the measurements performed by the other partners in frame of the project. The simulation comprehends the period between October 2017 and February 2019. For this period the most complete and suitable data set for the model calibration was available. Some of the hydrological, meteorological and morphological required input data are presented in Figure 45 and Figure 46. Some other important measurements that are required for the correct behaviour of the model are the bathymetry of the water body and the sediment rating curve. The latter describes the behavior of the sediment load (ton/a) or the sediment concentrations (kg/m³) in function of the incoming water discharges entering the reservoir. During the calibration phase, sensitivity analyses were performed in order to find the best fit or lowest Mean Absolute Error (MAE). For the calibration of the hydrodynamics, the best version of the model was the one with the lowest MAE when reproducing the temperature stratification over time measured at the water intake. For this point the simulated flow velocities at the intake where compared with the measured ones as well.

Using the reference simulation, the fundamental processes affecting the hydrodynamics and the sedimentation were studied through sensitivity analyses. Depending on the variation of the results with respect to the reference simulation, a rating of the most important processes and hence the indispensable input data for the model could be established. Or in other words: which data are difficult to measure and are not that important for the model quality or prediction capability. Those investigations were carried out in frame of one master thesis (Maudody, 2020) at IWG-WK under the close supervision of the main researchers in charge of the present work package. Their results are aimed to achieve the first specific objective presented in the previous section.

For the persecution of the second specific objective 16 simulations were carried out and compared to the reference simulation. The focus of this work was on the variation of the temporal resolution of the input data, e.g. the inflow water discharges and temperature were varied from daily to each 2 days resolution. Furthermore, the effect of the use of different data source e.g. ERA5 for the meteorological variables or several rating curves was also studied.

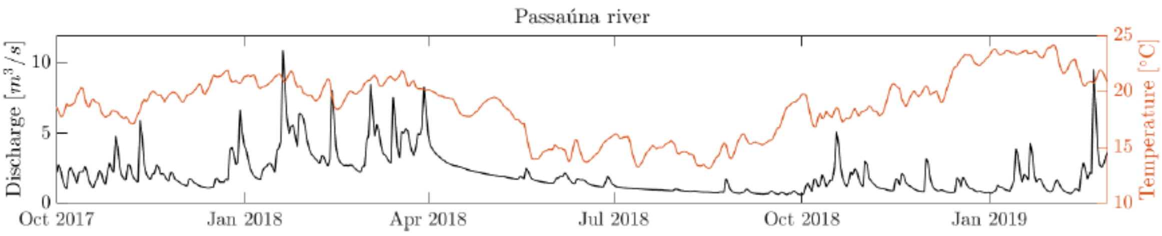


Figure 45: Simulated water discharge (black line) and corresponding temperature (red line) at the main reservoir inflow: Passaúna River.

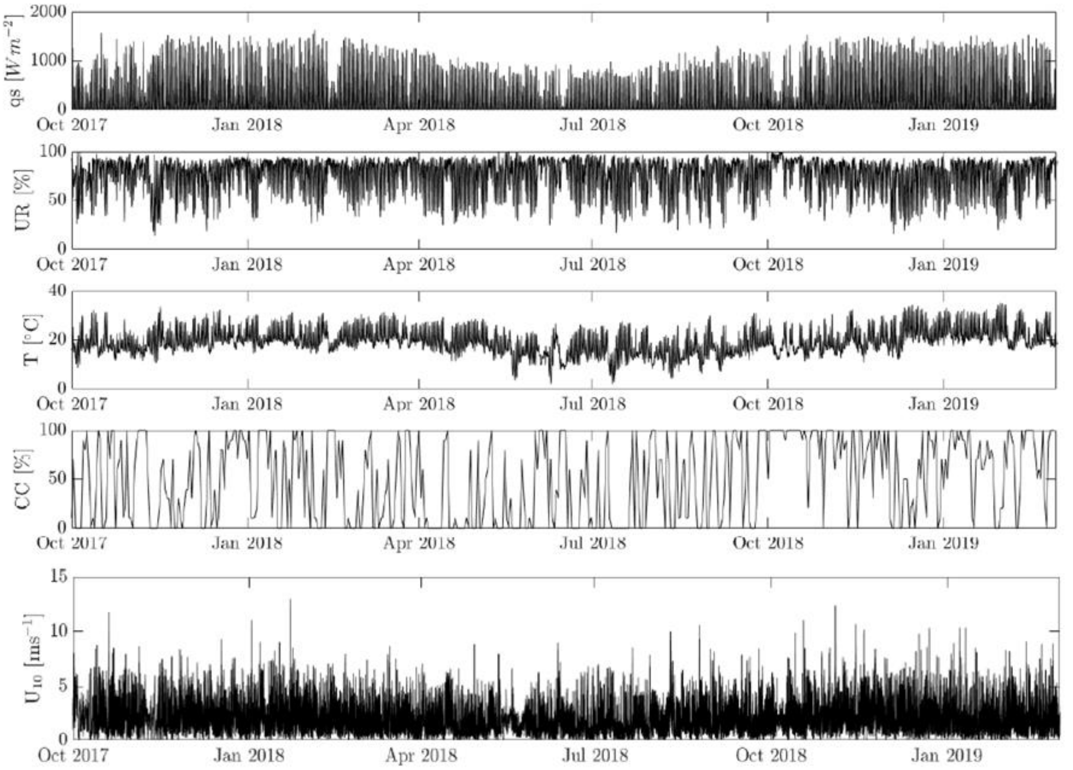


Figure 46: Meteorological parameters used as input data in the numerical model. From top to bottom: solar radiation, relative humidity, Air temperature, cloud coverage and wind speed at 10 m above the water surface.

The investigations on the model dimensionality and their repercussion on the results were divided in two parts: model interdimensionality in the simulation of the hydrodynamics and model interdimensionality in the simulation of the sedimentation. For the hydrodynamics a 1D model was set up using the software GLM (Hipsey, et al., 2019). For the model in two principal dimensions a lateral averaged 2D model was constructed and calibrated using the software CE-QUAL-W2 (Cole & Wells, 2015). The reference simulation was used as the representation of a 3D model. The models were compared regarding their capability of simulation the temperature stratification at the intake, here a mean average error was used as main statistic variable. The management of the 1D and 2D model was completely carried out by the Brazilian partner UFPR. Their results were obtained on the frame of the master thesis of Golyjeswsky, 2020 (2D Model) and Gomes, 2020 (1D Model). A very close cooperation with the main researcher of the WP6 was also achieved in the persecution of this objective.

For the study of the effect of the model interdimensionality on the sedimentation 0D, 1D and 3D simulations were carried out. For the 0D simulations some approaches were tested for the sedimentation patterns in the Passaúna reservoir e.g. the Brune Approach (Brune, 1953) and the Van Rijn Approach (Van Rijn, 2013). The 1D model was constructed using the widely applied software HEC-RAS (Brunner, 2016). For the 3D simulation Delft3D was employed. The 0D and 1D simulations were performed in the frame of the master thesis of Mees, 2020 and the study project of (Perez, 2020) both at IWG-WK.

5.3.3. Results

The intermediate and final results of the WP3 activities will be presented divided by their contribution to the persecution of the three specific objectives.

Determination of the crucial processes and related input data sets governing the hydrodynamics and sedimentation in reservoirs.

As mentioned in the partial report of the year 2019 (Zwischenbericht 2019 –KIT AP 3) two numerical grids were constructed a “rectangular” and a “curvilinear” grid in order to study the influence of a higher cell resolution at the area of the Ferraria Bridge with the aim of properly simulate the density currents caused by temperature differences. Both grids could manage to simulate well the hydrodynamics of the reservoir, including the density currents. In terms of sediment transport, the simulated deposition pattern using the curved grid was more similar to the measured one than when using the rectangular grid. For further investigations the curvilinear grid was selected (see flyer „Relevant aspects in the numerical modeling of the hydrodynamics and sedimentation in reservoirs”; Figure 1), to assure for any other hydrological scenario, that the underflow/interflow or overflow could be modeled as best as possible and also to get the most realistic representation of the sediment deposition patterns

During the calibration of the model the best set of parameters that allowed simulating the measured temperature and flow velocities at the withdrawal but also the parameters that had the highest effect on the variation of the results were investigated. The number of vertical layers was varied; it was found that the higher the number of layers was, the lower the MAE for the simulated temperatures at the cost of a high increase in the computational time. Nevertheless, it does not mean that a very high number of layers should be used, since at some point the variation on the MAE will be minimal and the computational time cost will be non-proportional higher. For example, the use of 20 layers instead of 15 layers results in a 0.02 °C difference in the MAE but in a difference of 13 hours in the computational time. Further parameters studied included the manning roughness coefficient, the wind drag coefficient, the background horizontal viscosity and diffusivity and the background vertical viscosity. The variation of these numerical and physical parameters showed to have a small effect on the results regarding the temperature. On the other hand, the change of two parameters included in the turbulence closure model, the background vertical diffusivity and the Ozmidov length scale, affected the results considerably. It makes sense since turbulence has an influence on mixing processes. The parameters Stanton number, Dalton number and secchi depth are included in the heat flux model for the air-water surface interaction and they all have a considerable impact on the results. The two first parameters can be considered calibration parameters. The secchi depth on the contrary can be measured; hence special attention has to payed to it during field campaigns. Figure 2 in the flyer “Relevant aspects in the numerical modeling of the hydrodynamics and sedimentation in reservoirs” shows the measured and simulated temperatures and their difference over time at the water intake for the simulation period for the best set of parameters. Figure 3 on the same Flyer shows a comparison of the measured and simulated velocities for the same simulation. Regarding the flow velocities, the two parameters that affected the most the simulated velocities at the intake were the background vertical viscosity and diffusivity, which can be considered calibration parameters since they can't be measured.

In order to study the influence of several physical and numerical parameters on the sedimentation in the Passaúna reservoir sensitivity analyses were performed. As already mentioned in the methods section, the results to be presented in the following were gained in frame of a master thesis (Maudody, 2020) under the close guidance and coordination of the two main researchers of the work package. The studied period comprehended six weeks. The variables time step, composition of the sediment incoming concentration, settling velocity of sediments, critical bed shear stress for sedimentation and the background horizontal diffusivity were investigated considering the action of wind but excluding the temperature effects. This combination is the typical set up for reservoir sedimentation model. The horizontal background eddy diffusivity showed the largest deviation from the reference simulation. At some point increasing this background value did not produce realistic results regarding the sedimentation. It was possible to define a range in which realistic results could still be generated with respect to the deposition quantities in the study area. This range laid between 0 and 0.001 m²/s, the value was therefore set to zero in the following.

A decisive influence on the deposited sediment layer and the deposition patterns resulted from the variation of the settling velocity. By reducing the settling velocities, the deposition in the reservoir decreased. Changing the critical bottom shear stress for sedimentation had a very notable influence on the place where most of the sediments deposit. A lower deposition shear stress shifted the onset of the deposition pattern downstream.

Changing the composition of the incoming sediments (i.e. the representative diameter of the size classes) allowed observing a small decrease in deposition and an increase in sedimentation downstream. However, these variations are due to the inherent change on the settling velocities. The other parameter that was investigated was the time step. Varying the time step from 6 out of 60 seconds had no effect on the results. This fact allows saving computational time by using the highest time step possible.

The obtained results were also compared to the available measurement data for SSC. Based on these results, it was determined that with a settling velocity of 0.01 mm/s, there was the best agreement between the simulated and measured suspended sediment concentrations. With a critical bottom shear stress for sedimentation of 0.001 N/m², a deposition pattern was established in the buffer, which was comparable to the measured data from the echo-sounding measurements. The model was therefore calibrated using these data. It needs to be highlighted, that the deposition pattern detected with the echo-sounding differs from the one modeled for the simulation period (see Figure 47). The simulated depositions show the classic delta shaped pattern in which the sediments deposit mainly at the first section of the reservoir whereas the measured values showed the highest deposition at the vicinity of the dam. There are several possible reasons for this: the echo-sounding is showing the results of 30 years of sedimentation, during this time span there were for sure flood events that are not being considered within the 17 months simulation period. These events could possibly introduce turbidity currents, which could possibly transport sediments from the main inflow until the dam. A second hypothesis is that the side arms near the dam are also contributing to sedimentation especially during flood events.

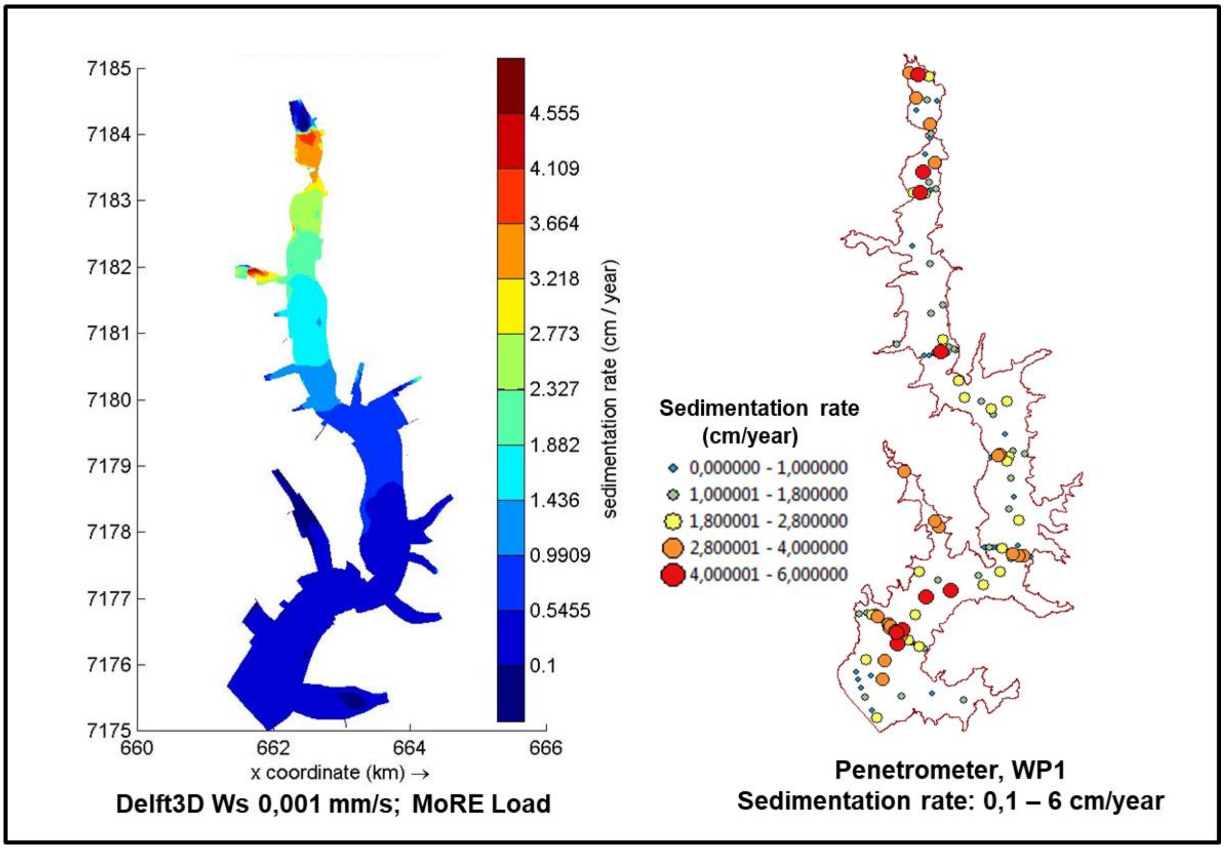


Figure 47. Comparison of simulated (left) and measured (right) deposition pattern.

Based on the calibrated model, the temperature influence on the sediment transport was investigated using the Sigma and Z-models. During these investigations, it was determined that the Z model was not suitable for modeling sediment transport in the study area. The low water levels towards the end of the modeling period as well as the low vertical resolution had a negative effect on the calculations: for those conditions no sediment would enter the model.

By comparing the results from the modeling of sediment transport with and without temperature influence using the Sigma model, it could be determined that the influence of temperature has a decisive effect on the flow velocities in the reservoir. During the modeling period, this resulted in higher velocities, especially in the lower layers. This led to an increased deposition of sediments in the downstream part of the Ferraria Bridge. It is important to remark that this is not the state of the art on the sediment modeling and it seems than for some cases like in Passaúna, it could have an effect on the results. On the other hand, for the Big Predam of the Dhünntalsperre the inclusion of temperature did not have an effect on the sedimentation processes.

The results of the hydrodynamics and sedimentation processes will be presented in two journal papers, which are under preparation.

Investigation of the lowest data resolution that still allows a good representation of the hydrodynamics and sedimentation

Parts of the results presented on this section were gained in frame of a master thesis (Mees, 2020) under the close guidance and coordination of the two main researchers of the work package. The results listed under this section took the high resolution or reference simulation as comparison standard for all the investigations. Tables 1 and 2 in the flyer "Study on the complexity reduction in the numerical modeling of hydrodynamics and sedimentation in reservoirs" show a summary of the investigated parameters for the hydrodynamics and for the sediment transport respectively.

In general, the reduction of the resolution and/or the variation in the variables that influence the heat flux between the water surface and the air showed the most significant differences. An exception constituted the reduction of meteorological data from 15 minutes to 1 hour; in this case no significant variation resulted on the simulated temperatures and velocities. The use of the ERA5 reanalysis data showed the highest differences regarding the reference simulation. This fact evidences a strong importance of measured data on the simulation results.

The use of other values for the secchi depth different to the one measured i.e. 0.5 m and 3.5 m instead of 2 m, resulted in opposite mean error, meaning that a lower secchi depth overestimates the calculated velocities of the full resolution simulation while the use of higher value underestimates them. Highest errors are observed in major part of deeper areas of the reservoir and at the constriction where the Ferraria Bridge is located. In this case, the simulation with the secchi depth of 0.5 m overestimated the velocities in higher depths and underestimated at Ferraria Bridge, with the contrary results when using the highest value for the same input parameter. This phenomenon could not be justified in this study, but it is an interesting topic for further research focusing on the impact of secchi depth on horizontal velocities.

The distribution of statistical errors through the depths adjacent to the reservoir intake demonstrated the high sensitivity of the numerical model to the input parameter secchi depth and provided help when analyzing their variation (see flyer "Study on the complexity reduction in the numerical modeling of hydrodynamics and sedimentation in reservoirs"; Figure 1). If the depth of the layer at which stratification begins is important (thermocline) for a given research project, these results suggest that the modeling of shorter periods with different secchi depths using Delft3D should be applied to achieve the best results. Another approach is to change the Delft3D code to implement the secchi depth as a parameter variating with time i.e. as time series input. This is an important advantage of Delft3d when compared to other software which are not available as open source.

The analyses of the results of the full resolution simulation and the reduced ones showed similar tendencies for the flow velocities: using meteorological parameters from reanalysis data of ERA5 (simulation ERA5) presented the highest deviation from the reference simulation, while the reduction of the resolution of the original measured heat flux parameters (simulation M1) did not affect the result in a significant manner. Deeper areas of the reservoir presented higher differences between the reference simulation and the reduced resolution simulations. The significantly better behavior of the one-hour resolution simulation compared to the ERA5 simulation illustrates the significance of measurement data, even if they are not available in high temporal resolution. The use of reanalysis data should be performed with prudence and its consistency should also be checked, even though their employment may be the best choice when working without measurement data.

Regarding the sediment transport processes the deposition patterns showed high sensitivity for the reduction of temporal resolution of rivers discharges, contrary to the results observed when analyzing the temperature and velocities in the reservoir. A possible explanation is the effect of longer periods with higher discharges (Figure 48) and consequently higher sediment inputs from the tributary rivers into the reservoir.

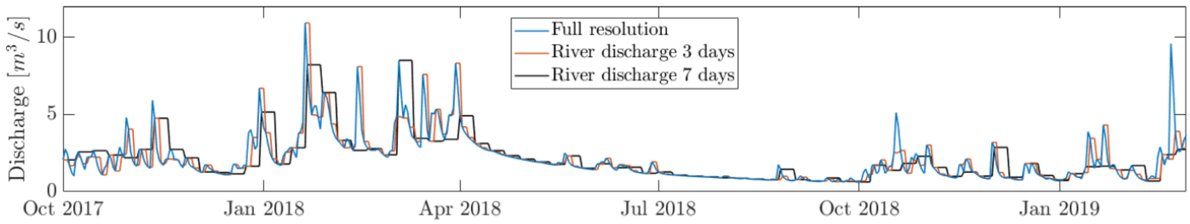


Figure 48. Resolution reduction of the water discharges through the Passaúna river inflow. Modified from (Mees, 2020)

A very interesting result was obtained when changing wind data, while the simulation with the reduced resolution of wind data from 15 min to 1 hour presented close results to the reference simulation, the simulation with ERA5 input data underestimated the deposition of sediment principally in the region between the Ferraria bridge and the Ferraria river, indicating that wind processes have an impact on deposition patterns and reanalysis data should also be used with caution also for sedimentation modeling (see flyer “Study on the complexity reduction in the numerical modeling of hydrodynamics and sedimentation in reservoirs”; Figure 2b)

In summary, it can be said that the effect of reducing the resolution of each parameter in a simulation is related to the processes in study. For temperature, the resolution for river discharge can be reduced and the focus should be on collecting measurement data for parameters associated with heat flux. Conversely, for sediment transport processes, the key focus should be on the resolution and quality of the input data of river discharge and the resulting sediment concentrations. For sedimentation processes as well as for hydrodynamics reanalysis data presented errors, but their ease of acquisition and low cost make them attractive when data are not available or for pre-feasibility studies. In all cases, it is critical to consider the characteristics of the reservoir in question in terms of its geometry, boundaries, and intended use when planning the numerical simulation of its inherent processes.

The results under this objective were submitted to be presented during the “Treffen junger WissenschaftlerInnen deutschsprachiger Wasserbauinstitute: JuWi “at the University of Aachen. The conference paper was accepted. Due to the COVID-19 situation the conference was postponed. After that the abstract was submitted to the IAHR World Congress 2021 in Granada, Spain. Due to the same reasons the conference was canceled. The main researcher of the WP3 is working on a paper to be submitted to a scientific journal. This paper will also include results from the study of model dimensionality regarding the sediment transport in order to reinforce the importance of the results.

Study of different model dimensionalities (3D, 2D, 1D and 0D)

Regarding the hydrodynamics the 1D, 2D and 3D model will be compared within a journal paper that is already under preparation. When comparing the temperatures all three models could simulate well the measurements at the intake (see flyer “Modeling of thermal stratification, density currents and water quality”; Figure 2). Nevertheless, the 3D model was the closest to the measured values. The second best was the 1D model. There is not a general answer to the question which dimensionality should be used. The modeler should first ask himself/herself which quantities at which locations are needed. For example, if only the temperature stratification at the intake is needed, then a 1D model is enough. But if also the flow velocities should be modeled, then a 1D model won’t be able to produce the answer. If the temperature stratification at several positions in the reservoir is needed and the reservoir geometry is larger than wider (like in the case of Passaúna), i.e. the cross-sectional variation of the parameters is not relevant. For those conditions a 2D lateral averaged numerical model will be suitable for the task. In general, a 3D model will allow simulating the hydrodynamic variables at any point of the reservoir independently of the reservoir geometry but at the cost of much higher computational time. Diagrams like the one the flyer “Relevant aspects in the numerical modeling of the hydrodynamics and sedimentation in reservoirs” in the Figure 3, which are useful for water management entities, can be created with a 3D model no matter which geometry the reservoir presents.

From the sedimentation analyses could be stated that the result of the 0D models for the deposition pattern in the Passaúna reservoir was similar to the results achieved with the 3D numerical simulations. For the 0D analyses the four approaches studied (see Methods section) resulted in a trap efficiency between 96 and 100% for the Passaúna reservoir (see flyer “Study on the complexity reduction in the numerical modeling of hydrodynamics and sedimentation in reservoirs”). Neither the 0D or the 3D models, showed good results when compared to the measured data. One effect that could be accountable for this is the lack of higher discharges as input data in comparison to measured incoming discharges, which were not entirely well reproduced by the LARSIM model, this hypothesis is based on the results of the simulation of turbidity currents. Since they revealed the largest disparities in the deposition pattern. For this scenario, less sediment was deposited in the northern part or predam of the reservoir and more sediment at the region after the Ferraria Bridge, indicating possible effects of erosion due to high water inflows. This is a significant topic for potential future research, as the impact of density currents in is not well defined. 0D models for sediment deposition patterns should only be used as preliminary studies to reservoir construction projects because the use of averaged values influences more complex issues such as erosion processes during high runoff events.

When studying the implementation of the 1D HEC-RAS model a simulation with exactly the same cohesive parameters as the 3D model was set up in order to compare the two dimensionalities. A comparison was made between the 1D model output and volume changes based on soil cores and a 3D numerical model. In both the 3D simulation and HEC-RAS, a few similar sediment deposition trends are evident in the upper northern portion of the reservoir (see flyer "Study on the complexity reduction in the numerical modeling of hydrodynamics and sedimentation in reservoirs"; Figure 4). There was nonetheless no agreement between the sediment deposition along the reservoir with the HEC-RAS simulation and the measured data with echo-sounding. As for the 3D model, it could not be achieved to use a 1D numerical model to simulate the deposition of fine sediments in the vicinity of the dam. The main advantage of this software is that it is able to simulate sediment transport over several decades in short computational time. However, it needs to be considered that a 1D model does not account for turbulence, secondary flows, lateral flows, turbidity currents stratification and mixing processes, or some vertical velocities that could lead to transport of more sediment near the dam and a more even distribution of sediment.

According to the results of the studies for the modeling of sediment transport in the Passaúna reservoir the further use of a 3D-numerical tool is advised. The complex interactions between hydrodynamics and sediment particles can't sufficiently described with lower dimensionalities.

Problems/obstacles

For the modelers the main problem when studying the hydrodynamics of the Passaúna reservoir was the water balance. The water balance is the difference between the amount of water leaving and entering the reservoir for a given time period. The change in the water volume for a time step and the use of a water level-volume curve should then allow the determination of the corresponding water level in the reservoir and in the best case it should also coincide with the measured water level. When the measured and calculated water levels are not matching, it is said that the water balance is not closing. This is the regular case for a reservoir and normally up to 10% surplus or deficit of water can be expected at most. This water unbalance is normally due to uncertainties in the estimation of the water fluxes in the system. The Passaúna reservoir was not the exception; its water balance was not closing. Using all the measured data, modeled incoming discharges and estimated evaporation for some time periods a lot of water was missing: approx. 70% of all inflows. This is an unusually large volume. To try to solve this problem all the terms included in the water balance were investigated. At the end the discharge through the spillway was corrected using the proper hydraulic formula after Polleni and also the discharge through the ground outlet was corrected. Those two aspects contributed to improve the water balance but not to completely close it. Still water is missing for some time periods but the models (1D, 2D and 3D) can all reproduce well the hydrodynamics despite of this.

The second main problem emerged when studying the sediment transport at the Passaúna reservoir. One of the most important input data, if not the most important, to correctly reproduce the volume and patterns is the amount of sediment entering the reservoir in function of time i.e. the sediment rating curve. For Passaúna there were three available rating curves: one derived based on historical data (Rauen, Oliveira, & Galdino, 2017), the second one based on measured data by the University of Positivo in Brazil during a high discharges event of three days and the third one based on modeled data of the MoRE software provided by WP 1. None of the curves was able to reproduce the necessary amount of sediments to match the deposited sediment volumes founded by the WP 1using the echo-sounding technique. The curve derived using the MoRE Data was the nearer to it and for this reason this data was used in most of the simulations. This problem also highlighted that accurate and high-resolution data is sometimes indispensable in order to set up a robust model, since sediment transport itself already involves complexes processes.

Those two main problems provided important information that actually contributes to main objective of the project. They let modelers know which data should be improved and which can be indulged during the preprocessing phase of the input data.

Literature:

Ahlfeld, D., Joaquin, A., Tobiason, J., & Mas, D. (December 2003). Case Study: Impact of Reservoir Stratification on Interflow Travel Time. *Journal of Hydraulic Engineering*.

Annandale, G., Morris, G., & Karki, P. (2016). *Extending the life of reservoirs. Sustainable sediment management for dams and run-of-river hydropower.* Washington D.C.: World Bank Group (Directions in development. Energy and mining).

Brune, G. (1953). Trap efficiency of reservoirs. *Trans American Geophysical UNion 34 (3)*, S. 407-418.

Brunner, G. (2016). *Hec-ras, river analysis system hydraulic reference manual: Version 5.0.*

Chanudet, V. e. (2012). Application of a three-dimensional hydrodynamic model to the Nam Theun 2 Reservoir (Lao PDR). *Journal of Great Lakes Research*.

Cole, T., & Wells, S. (2015). *CE-QUAL-W2: A two-dimensional, laterally averaged, hydrodynamic and water quality model, version 3.72.* Portland, OR: Department of Civil and Environmental Engineering, Portland State University.

Deltares. (2014). *Delft3D-FLOW - Simulation of multi-dimensional hydrodynamic flows and transport phenomena, including sediments - UserManual.* Delft: WL | Delft Hydraulics,.

Galli, C., & Abe, D. (2010). *Disponibilidade, poluição e eutrofização das águas.* São Paulo: Instituto de Botânica (Águas do Brasil: Análises Estratégicas).

Golyjeswsky, O. (2020). *SIMULATION OF THERMAL STRATIFICATION USING THE A 2DV (CE-QUAL-W2)AND A 3D (DELFT3D) MODEL. THE CASE STUDY: PASSAÚNA RESERVOIR.* Curitiba, Brazil: University of Paraná (UFPR).

Gomes, G. (2020). *WATER QUALITY MODELING IN A SUBTROPICAL WATER SUPPLY RESERVOIR.* Curitiba, Brazil: Federal University of Paraná (UFPR).

Haun, S., Kjærås, H., Løvfall, S., & Olsen, N. R. (2013). Three-dimensional measurements and numerical modelling of suspended sediments in a hydropower reservoir. *Journal of Hydrology*.

Hillebrand, G., Klassen, I., & Olsen, N. (2017). 3D CFD modelling of velocities and sediment transport in the Iffezheim hydropower reservoir. *Hydrology Research*.

Hipsey, M., Bruce, L., Boon, C., Busch, B., Carey, C. C., Hamilton, D. P., . . . and Winslow, L. A. (2019). A General Lake Model (GLM 3.0) for linking with high-frequency sensor data from the Global Lake Ecological Observatory Network (GLEON). *Geosci. Model Dev., 12, 473–523, https://doi.org/10.5194/gmd-12-473-2019*.

Jakobs, A. (2018). *3D-numerische Modellierung des Feinsedimenttransports unter Berücksichtigung von Schichtungs- und Mischungsprozessen für die große Vorsperre der Dhünntalsperre.* Karlsruher Institut für Technologie (KIT), Karlsruhe. Institut für Wasser und Gewässerentwicklung: Fachbereich Wasserwirtschaft und Kulturtechnik.

Klassen, I. (2017). *Three-dimensional Numerical Modeling of Cohesive Sediment Flocculation Processes in Turbulent Flows.* Karlsruhe.

MacIntyre, S., Flynn, K. M., Jellison, R., & Romero, J. R. (1999). Boundary mixing and nutrient fluxes in Mono Lake, California. *Limnol. Oceanogr. 44 (3), pp. 512–529. DOI: 10.4319/lo.1999.44.3.0512.*

Maudody, M. (2020). *Analysen der Hydrodynamik und des Sedimenttransports in Stauseen unter Berücksichtigung des Wärmetransports auf Basis 3D-numerischer Simulation.* Karlsruher Institut für Technologie (KIT) - Institut für Wasser un Gewässerentwicklung, Fachbereich Wasserwirtschaft und Kulturtechnik.

Mees, D. (2020). *Complexity reduction of three-dimensional numerical modelling of the hydrodynamics and sediment transport in water reservoirs considering the heat transport. Study case: Passaúna reservoir in Brazil.* Karlsruher Institut für Technologie (KIT)-Institut für Wasser und Gewässerentwicklung: Fachbereich Wasserwirtschaft und Kulturtechnik.

Ministerio de Minas e, E. (2013). *Balanço Energético Nacional. In Relatório final.*

Omer, A., Ali, Y., Roelvink, J., Dastgheib, A., Paron, P., & Crosato, A. (2015). Modelling of sedimentation processes inside Roseires Reservoir (Sudan). *Earth Surface Dynamics*.

Perez, J. (2020). *1D numerical simulation of the hydrodynamicsand sediment transport.* Karlsruher Institute für Technologie. Institut für Wasser und Gewässerentwicklung: Fachbereich Wasserwirtschaft und Kulturtechnik.

Polli, B., & Bleninger, T. (2019). Comparison of 1D and 3D reservoir heat transport models and temperature effects on mass transport. *Brazilian Journal of Water Resources*, S. 19.

Rauen, W., Oliveira, C., & Galdino, M. (2017). CARACTERIZAÇÃO HIDROSSEDIMENTOLÓGICA DO RIO PASSAUNA,PR, BRASIL, A PARTIR DE DADOS HISTÓRICOS. (S. 8). Florianopolis: ABRH.

Schleiss, A., De Cesare, G., Franca, M., & Pfister, M. (2014). Reservoir Sedimentation. *River Flow 2014.* Taylor and Francis Group.

Taveira-Pinto, F., Lameiro, L., Moreira, A., Carvalho, A., & Figueuredo, N. (2014). Global analysis of the sedimentation volume on Portuguese reservoirs. *River Flow 2014* (S. 237-244). LAUSANNE, SWITZERLAND: CRC Press.

Van Rijn, L. (2013). *Sedimentation of Sand an Mud in Reservoir and Rivers*. Abgerufen am November 2019 von http://www.leovanrijn-sediment.com

Zhang, F., Zhang, H., Bertone, E., Stewart, R., Lemckert, C., & Cinque, K. (24. May 2020). Numerical study of the thermal structure of a stratified temperate monomictic drinking water reservoir. *Journal of Hydrology: Regional Studies*, S. 21.

Zhang, R., & Wu, B. (2019). Enviromental Impacts of High Water Turbidity of the niulan River to Dianchi Lake Water Diversion Project. *Journal of Enviromental Engineering*.

5.3.4. Flyers

MuDak-WRM

FONA Research for Sustainable Development BMBF

SPONSORED BY THE Federal Ministry of Education and Research

3D-numerical modelling of suspended sediment transport in the Passaúna Reservoir

Modelling sediment deposition; volumes and patterns

Context

The construction of a dam always represents a major change in the enviroments related to the once free flowing river. The suspended sediments that are transported by the river settle upstream of the dam due to the low flow velocities regime governing these water bodys. The deposition of fine sediments causes loss in the storage volume of the reservoir. The fine cohesive sediments also have the property to absorb contaminats, acting as a source of pollutants, which can be relased into the reservoir (see Fig.1).

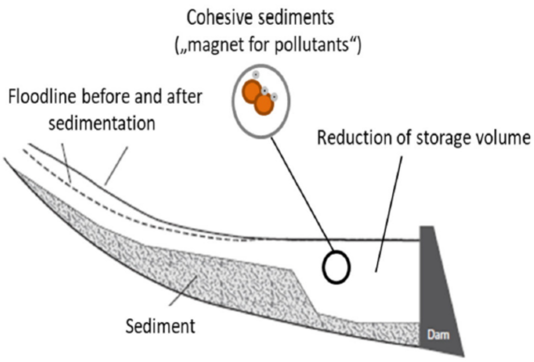


Figure 1. Issues caused by sedimentation affecting the management of reservoirs (adapted after: Annandale et al. 2016)

In frame of the project MuDaK-WRM three dimensional numerical models were set up for a Brazilian reservoir. These tools help water and sanitary companies to make decisions regarding the sediment management in the reservoirs. Such models are calibrated and validated using data from field measurements e.g. the sedimentation rates and deposition patterns (See Fig 2).

Objectives/Goals

- ✓ Sedimentation rate for the reservoir under specified boundary conditions (cm/year)
- ✓ Spatial distribution of deposited sediments

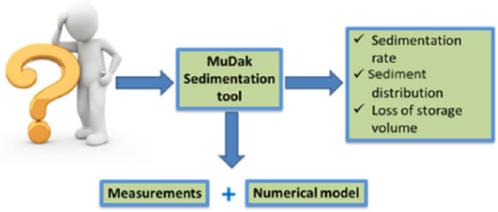


Figure 2. Schema of the sedimentation tool offered by MuDak WRM

Methods

The software Delft3D (Deltares, 2016)[1] was implemented for the numerical simulations within the present work. For the simulation of sediment transport in the Passaúna reservoir a curvilinear grid with 10 Sigma- layers (in total 28980 grid cells) was used. A total of 65 tributaries to the Passaúna reservoir are included in the model. For the modeled scenarios a simulation period of 17 months was defined (October 2017 - February 2019).

Several rating curves were used as the temporal distribution of the quantities of incoming sediments in function of the discharge at the inflows. Two sediment fractions (one cohesive, one non-cohesive) were defined for the simulation; this decision was based on data from sediment cores of the reservoir. The simulations were carried out taking into account the effects of wind.

Output of Delft3D

In the following some results for the reservoir are presented. Figure 3. shows the simulated sedimentation rates and their spatial variations in the reservoir. This simulation was set up using a rating curve based on sediment loads calculated in frame of the project with MoRE (Modelling of Regionalized Emissions). The average incoming sediment concentration at the main inflow is 1600 mg/l for this rating curve.

The model simulated a sedimentation rate between 0 and 4.6 cm/year. According to the simulation a total volume of 70898 m^3 of sediment was deposited in the reservoir during one year. Sauniti et al. 2002[2] meas-

1.Deltares,2016. Delft3D Flow: Simulation of multi-dimensional hydrodynamic flows and transport phenomena, including sediments.
2. SAUNITI, R. M.; FERNANDES, L. A.; BITTECOURT, A. V. L. Estudo do assoreamento dreservatório da barragem do rio Passaúna - Curitiba (PR). Boletim Paranaense de Geociências, v. 54,p. 65-82, 2004.

ured a sedimentation rate between 0.66 to 3.04 cm/year in the Passaúna reservoir. Within the frame of the MuDak-Project sedimentation rates between 0.1 and 6.0 cm/year were measured with a dynamic penetrometer. Also in frame of the project sediment traps were deployed into the water body. They showed decreasing sedimentation rates from the northern region of the reservoir to the dam. In the model the same tendency is found.

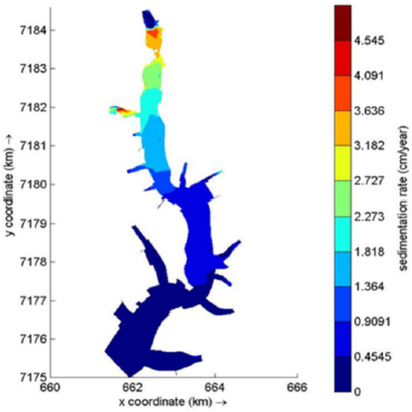


Figure 3. Simualted sedimentation rates for the Passaúna Reservoir using rating curve based on MoRE.

Fig. 4 shows the sedimentation rates simulated using a different rating curve. This rating cuve was based on data measured by the National Agency of Water (ANA) and AGUASPARANA. The average incoming sediment concentration at the main inflow was set to 70 mg/l. The resulting sedimentation rates vary between 0 and 0.25 cm/year.

In the Fig. 5 we can observe the simulated suspended sediment concentrations at the water surface for a specific date (14.02.2018) for both simulations.

Discussion

As can be appreciated in the presented results, the rating curve to be employed for the model is extremely important. Since depending on these input parameter the sedimentation rates, its spatial distribution and also the suspended sediment concentrations will vary.

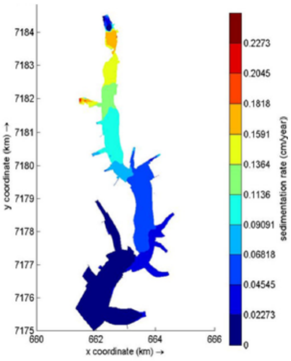


Figure 4. Simulated sedimentation rates for the Passaúna Reservoir using rating curve based on data of the ANA and AGUASPARANA.

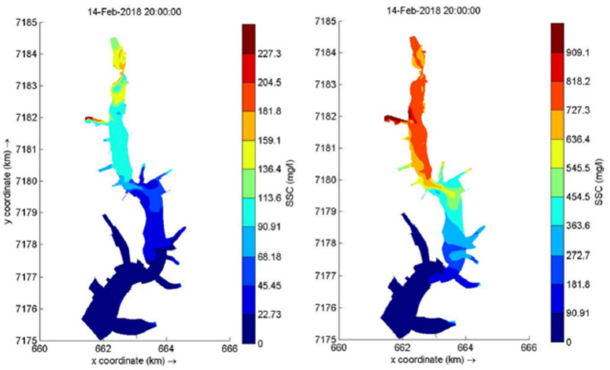


Figure 5. Simulated suspended solid concentrations at the water surface for both simulations. Left: using rating curve based on measuremnt of the ANA and AGUASSANEPAR. Right : using rating curve based on MoRE.

Innovation/Outlook

- ✓ The numerical model can be used to simulate the system response of the reservoir to different inflow scenarios and boundary conditions where the input parameters are changing.
- ✓ Simulation of deposition patterns and deposition rates for reservoir management
- ✓ Simulation of suspended sediment concentrations.

Authors Wendy Gonzalez, Tobias Bleninger and Frank Seidel
Contact wendy.otero@kit.edu

Funded by Federal Ministry of Education and Research, BMBF
Web www.mudak-wrm.kit.edu

MuDak-WRM

FONA Research for Sustainable Development BMBF — Sponsored by the Federal Ministry of Education and Research

Relevant aspects in the numerical modelling of the hydrodynamics and sedimentation in reservoirs

Identification of the most decisive numerical and physical parameters for the numerical modelling with a 3D software: Delft 3D.

Context

The use of numerical models for the prediction and study of the processes that take place in water bodies is an practice being applied with higher frequency in engineering projects. The appropriate modelling of the hydrodynamics of a reservoir includes, between others, the simulation of its thermal structure, flow velocities, and density stratification. The summarized results on this flyer give a guide to modelers to pre-identify calibration parameters or processes that should be handled with caution on the frame of the 3D-numerical simulation of a water reservoir.

Objectives

- Summarize capabilities of the 3D model regarding hydrodynamics
- Summarize most relevant parameters for the hydrodynamics and sediment transport modelling.

Methods

Set up and calibration of the 3D model, comparing the simulated vertical temperature profile at the water intake and the respective measurements. Measured and simulated flow velocities were also analyzed. Mean absolute errors (MAE) where calculated with respect to the measurements.

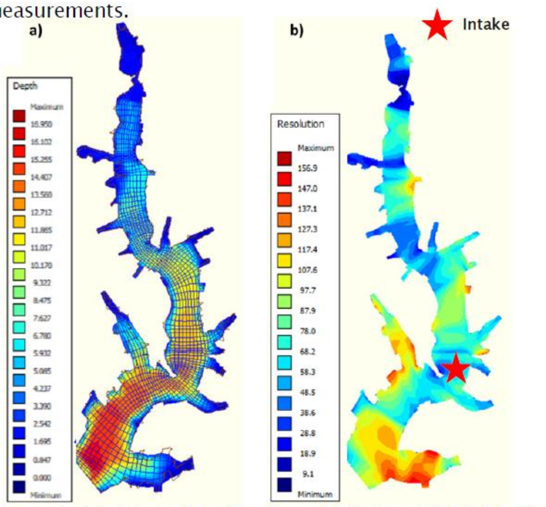


Figure 1: (a) *Interpolated bathymetry (m) and (b) Grid cells resolution (m) and position of the water intake*

Results

Temperature:

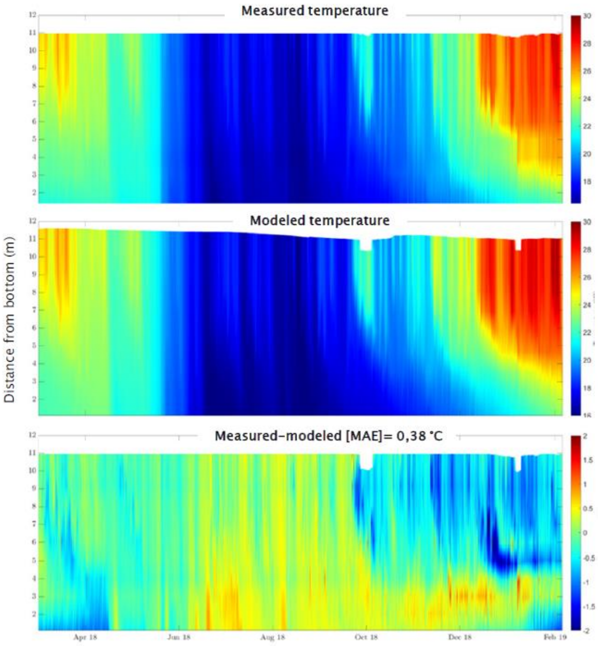


Figure 2: Temperature profiles measured and simulated at the water intake region and differences between both of them.

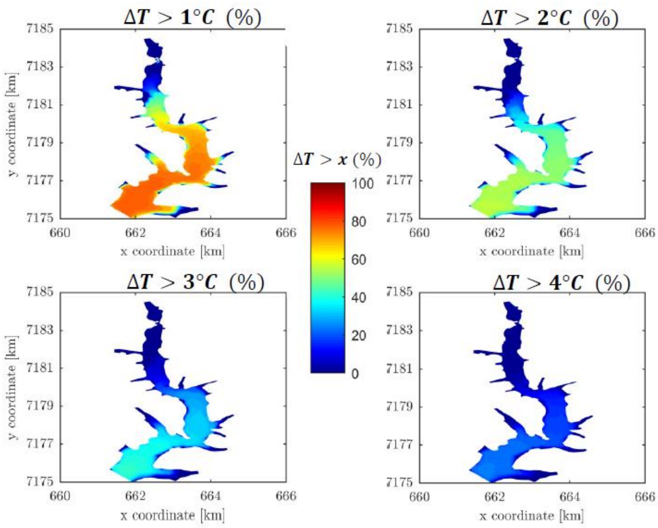


Figure 3: Period of time (in %) that a certain temperature gradient (surface-bottom) is expected in Passaúna Reservoir during the simulation period (01.10.2017 until 28.02.2019)

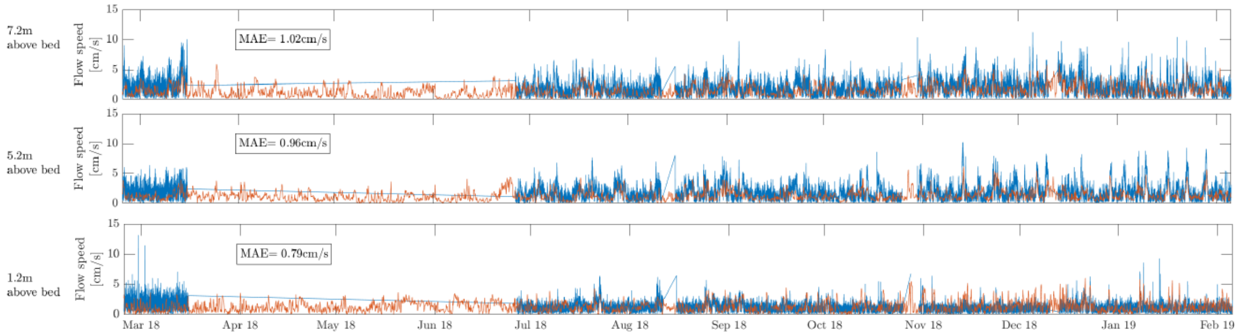


Figure 4: Measured (orange lines) and simulated (blue lines) flow velocities at the intake region for the indicated vertical positions.

In the frame of the study the most relevant parameters for the **hydrodynamics** were identified as follows: background vertical diffusivity, Ozmidov length scale, Dalton number, Stanton number and Secchi depth. All of these parameters influence either the turbulence modelling (the two first mentioned) or the heat flux model for the heat exchange between the water surface and the air. Flow velocities did not seem to show great changes while variating the investigated parameters. The highest variation was obtained when changing the background vertical diffusivity. Processes like wind (wind speed and direction) and water surface heat exchange (meteorological data) can severely affect the simulation of mixing and stratification processes.

For the modelling of **sedimentation** patterns and volumes the most important input data is the sediment rating curve. Further parameters like the settling velocity of sediments, the bed shear stress for sedimentation and the background horizontal diffusivity had a decisive impact on the modelling results. For the sediment transport the inclusion of wind effects is important since it has a significant impact on deposition patterns.

For the Passaúna Reservoir, it was found that the inclusion of temperature effects can affect the deposition pattern (see Figure 5).

Also the use of a sigma or a Z-model for the vertical layering influences the deposition pattern (see Figure 6).

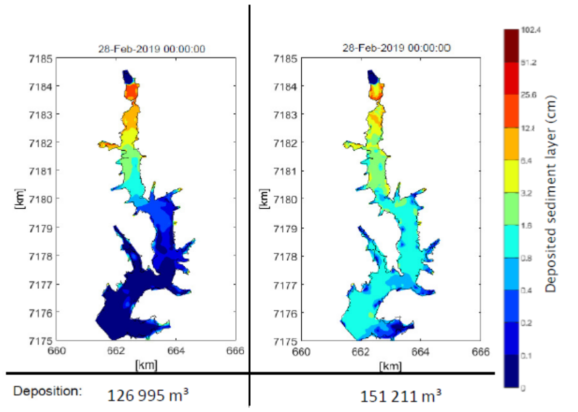


Figure 5 simulated deposition with sigma model without inclusion (left) and with inclusion (right) of temperature effects.

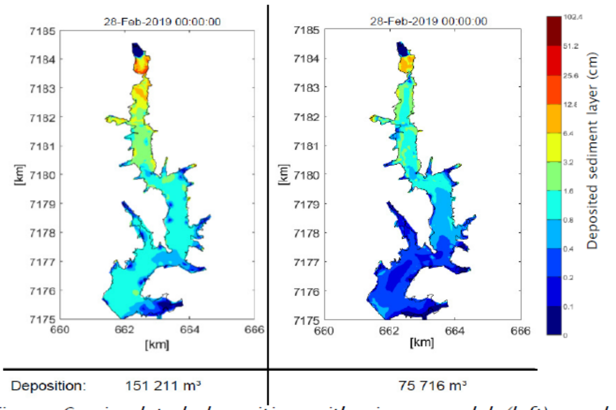


Figure 6. simulated deposition with sigma model (left) and Z-model (right) both with temperature effects.

Innovations

- ➢ Guide for field campaigns and recollection of field data.
- ➢ Guide for modelers for the preprocessing and calibration phase.

Authors Wendy Gonzalez, Maseh Maudody, Frank Seidel and Tobias Bleninger
Contact wendy.otero@kit.edu
Date 29-12-2020

Financed by Federal Ministry of Education and Research, BMBF
Site www.mudak-wrm.kit.edu

MuDak-WRM

FONA Research for Sustainable Development BMBF — Sponsored by the Federal Ministry of Education and Research

Study on the complexity reduction in the numerical modelling of the hydrodynamics and sedimentation in reservoirs

Investigation of the data resolution that stills allows a good representation of the hydrodynamics and sedimentation. Comparison with further model dimensionalities 0D and 1D.

Context

The set up and calibration of good performing numerical models require a high quantity of input data with high temporal and special resolution. The complexity and the amount of data required are rarely measured in regular campaigns or with monitoring stations. The demand for data usually leads to the implementation of comprehensive measurement campaigns, which translates into personnel costs and time.

Objectives

- Investigation of the minimumtemporal resolution for selected input data.
- Effect of the use of alternative data sources (e.g. ERA5 meteorological data) or "wrong" data.
- Exploration of different model dimensionalities for the sediment transport.

Methods

For the present study the Passaúna reservoir is used as a study case with high resolution measured datasets. Within the present study the data set resolution was reduced and the quality of the simulation was evaluated. The tables 1and 2 summarize the investigated parameters.

For the investigation of the model dimensionality several 0D approaches were tested: Brune (1953), Borland (1971), Eysink and Vermaas (1981) and van Rijn (2013). Furhtermore a 1D model with the software HEC-RAS was set up and extensively studied.

Table 1. Reduced resolution simulations used for hydrodynamics and temperature.

Parameter	Original value/ resolution	New values/ resolution
Rivers discharges	1 day	3 days
		7 days
Meteorological parameters	15 minutes	1 hour
		ERA5 reanalysis: 1 hour
Secchi depth	2 m	0.5 m
		3.5 m

Table 2. Reduced resolution simulations used for sediment transport

Parameter	Original value/resolution	New values/ resolution
Rivers discharges	1 day	3 days
		7 days
		1 hour
Wind	15 minutes	ERA5 reanalysis: 1 hour
Fictive turbidity current	Q Variable (from LARSIM model)	3 x Q (for specific dates)
	SSC Variable (from MoRE model)	3 x SSC (for specific dates)
Fictive sediment concentration	SSC Variable (from MuDak Project)	2 x SSC

Results

Hydrodynamics: changing the resolution of the river discharges and temperatures and using one hour resolution meteorological data had little influence on the simulated velocities and temperatures. Using reanalysis data from ERA5 and employing "wrong" values for the secchi depth (see Figure 1) presented the highest mean errors when comparing the simulates velocities and temperatures to the high resolution simulation.

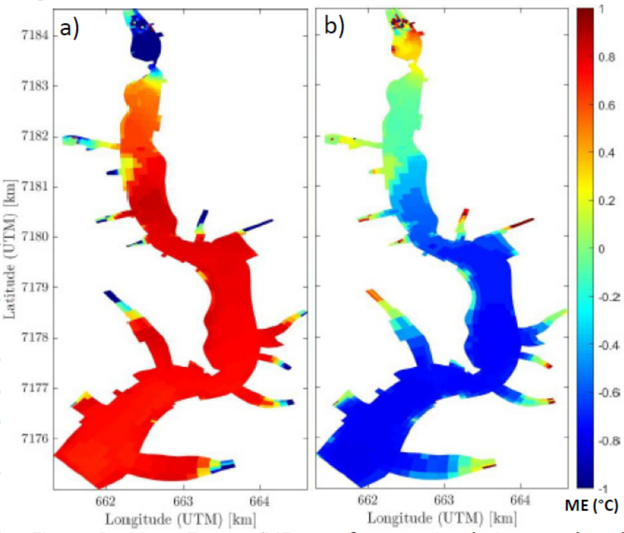


Figure 1. *Mean Errors (ME = reference simulation - reduced resolution simulation) for a) secchi depth 0.5 m and b) secchi depth 3.5m. Positive mean error: underestimation of the simulated temperatures with respect to the reference simulation.*

<u>Sedimentation</u>: when analyzing the numerical simulations showed in Table 2. the sediment volume deposition is very similar, with exception of simulation with fictive rating curves, which had doubled volume deposition in comparison to the reference as expected. It may remind the modelers about the importance of the rating curve for the results. Regarding the sensitivity to the resolution reduction for the numerical simulations, river discharges and its inherent sediment inputs had an effect on the results which was not observed in the hydrodynamics. The implementation of a fictive turbidity current, as well as ERA5 data also showed influences on the performance of the simulation (see Figure 2).

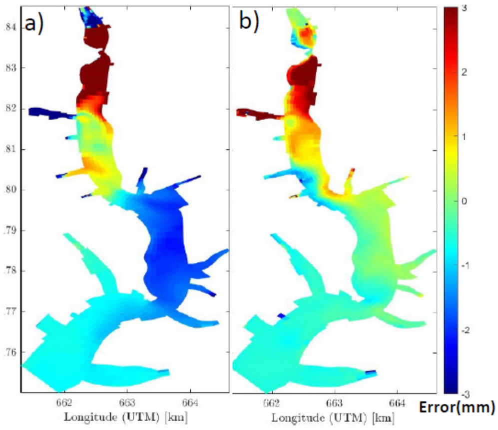


Figure 2. *Errors (reference simulation – reduced resolution) regarding the deposited sediment layer for a) fictive turbidity current and b) use of ERA5 data.*

<u>Dimensionality</u>: for the 0D analyses all of the four approaches studied (see Methods section) resulted in a trap efficiency between 96 and 100% for the Passaúna Reservoir. The table below shows the calculated distribution of sediments in the sections of Figure. 3 according to the different methods.

Table 1. Deposition patterns for the 0D approaches

0D approach / Section	Borland (1971)	Eysink and Vermaas (1981)	Van Rijn (2013)
	deposited cohesive/non -cohesive sediment (%)		
1	18/100	26/100	11/100
2	70/100	100/100	99/100
3	77/100	100/100	100/100
4	82/100	100/100	100/100

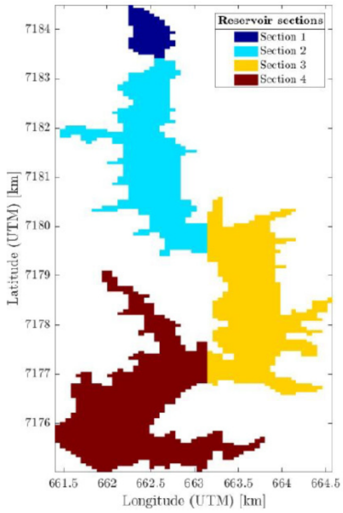


Figure 3. *Defined sections used for 0D approaches to evaluate deposition patterns.*

<u>Dimensionality</u>: the 1D model showed similarities to the 3D and 0D delta deposition patterns (see Figure 4). Nevertheless the 0D and 1D approach are not suitable for short simulations periods with occurrence of special processes e.g. turbidity currents, lateral flows, density currents, stratification and mixing or even vertical velocities that will result in transport of more sediments further into the southern part of the reservoir. For this reason 0D and 1D approaches are advised only for pre-feasibility studies in order to evaluate the trap efficiency of the reservoir.

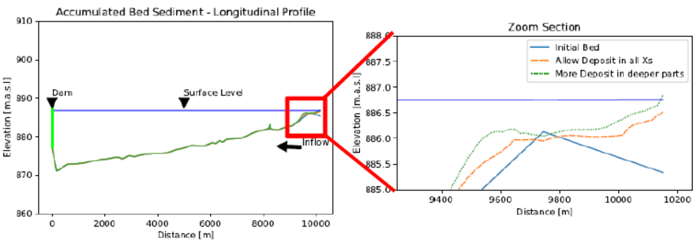


Figure 4. *Delta deposition at the reservoir according to 1D approach.*

Innovations

- Guide for field campaigns and recollection of field data
- Guide for modelers for the preprocessing phase previous to the calibration

Authors Wendy Gonzalez, Diogo Mees Delfes Varela, Javier Pérez and Frank Seidel
Contact wendy.otero@kit.edu
Acknowledgements and collaboration : Tobias Bleninger
Financed by Federal Ministry of Education and Research, BMBF
Date 29-12-2020
Site www.mudak-wrm.kit.edu

MuDak-WRM

FONA Research for Sustainable Development BMBF — Sponsored by the Federal Ministry of Education and Research

Modeling of thermal stratification, density currents and water quality

Use of mathematical models to represent the hydrodynamics and water quality of the Passaúna reservoir.

Context

Models are useful tools to complement measurement data. Scenarios can be tested with different operational and management strategies.

Objectives

- Spatial and temporal representation of physical and chemical variables
- Determination of water quality using indexes and mapping of results.
- Prediction of changes in water quality for situations where measured data is not available.
- Evaluation of the models' performance and determination of the minimum monitoring aiming at the optimized operation of the reservoir.

Methods

Construction and calibration of hydrodynamic and water quality models with different resolutions using field measured data. Subsequent evaluation and comparison of results, limitations and potential of the models used. Enabling the integration and interpolation of measured water quality data in monitoring points and forecast variations through the construction of scenarios, which can benefit management decisions.

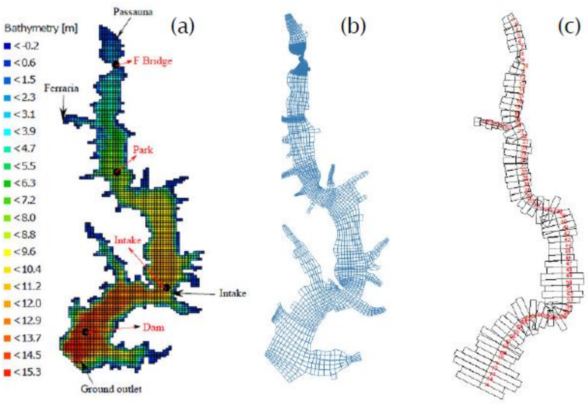


Figure 1: (a) *Interpolated bathymetry for use in Delft3D, with identification of the main monitoring points with red arrows. (b) Grid of the Delft3D model. (c) Grid of the CE-QUAL-W2 model.*

	Software	Details
0D	Excel/Matlab	Perfectly mixed reactor
1D	GLM	Vertical profiles
2D	CE-QUAL-W2	Homogeneous in cross sections
3D	Delft3D	Inclusion of the water quality module in the hydrodynamic model

Results

Temperature:

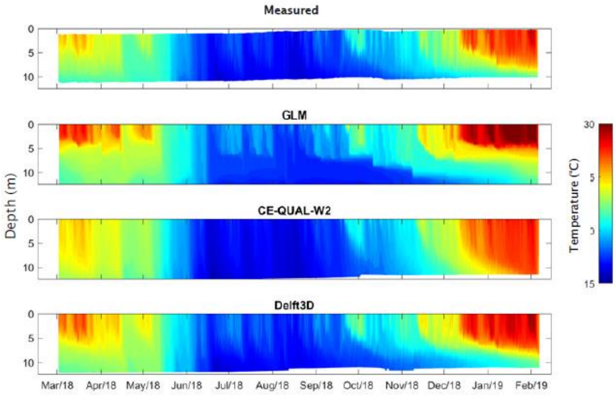


Figure 2: Temperature profiles measured and simulated in the water intake region. In the three models it is possible to observe the main mixing and stratification pattern throughout the year, however more detailed analyses are needed.

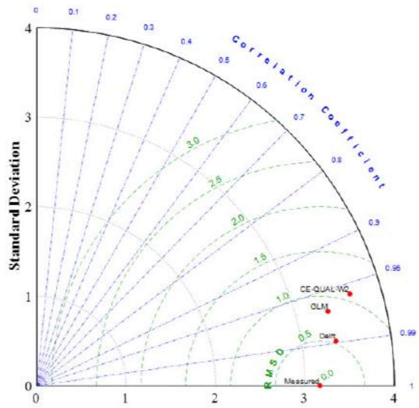


Figure 3: Taylor diagram comparing standard deviation, correlation and mean square error between simulations and temperature measurements in the water intake region.

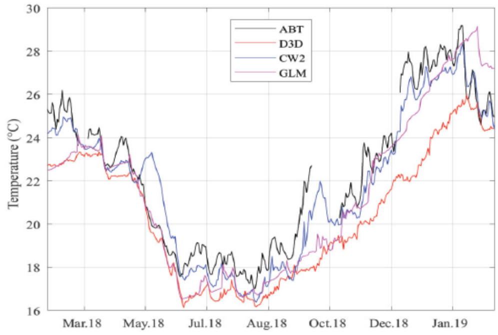
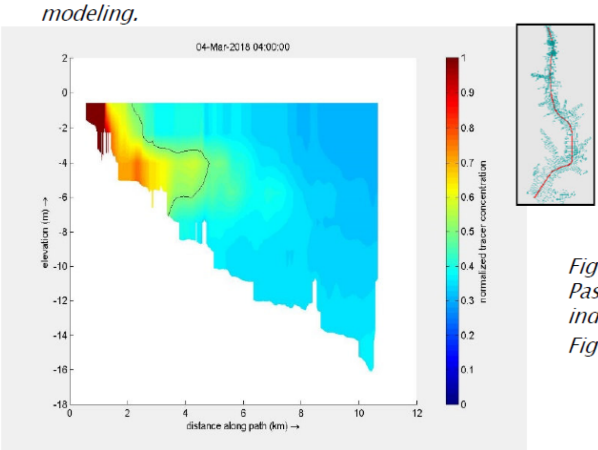


Figure 4: Measured temperature (ABT), vs. simulation results with 3D (D3D), 2D (CW2) and 1D (GLM) modeling.



Density currents CE-QUAL-W2 and Delft3D:

- ➢ The evaluation of the density currents helps to identify the location, in terms of depth, of the river entrance. This identification is important for tracking organic matter nutrients that will interfere with water quality.

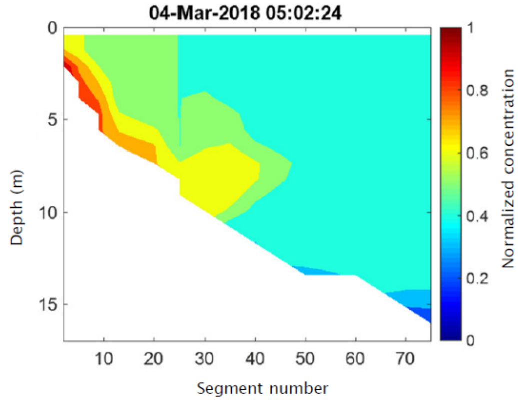
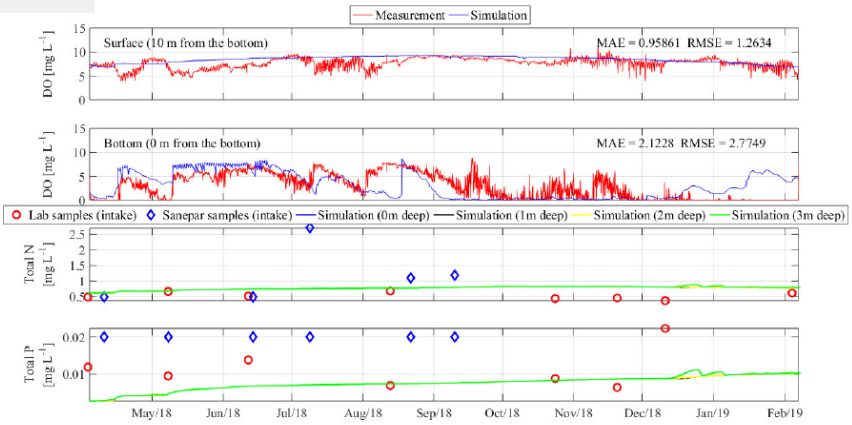


Figure 5: Result of the simulation with CE-QUAL-W2 of the Passaúna River tracer distribution entering the reservoir, indicating an interflow.

Figure 6: left side; Delft3D result for the same simulation.

Water Quality 1D (GLM-AED) :

- ➢ Results of water quality modeling simulation compared to laboratory analysis.
- ➢ Simulation results completed data between field campaigns



Innovations

- ➢ Develop strategy to improve management using modeling predictions.
- ➢ Through the analysis of the model results, determine the minimum data needed to operate the reservoir.

Authors Tobias Bleninger, Wendy Gonzalez, Gabriela Gomes, Luziadne, Kotsuka, Mayra, Ishikawa and Orides Golyjeswsky

Contact Tobias.bleninger@gmail.com | luzi.kotsuka@gmail.com

Date 02-12-2020

Site www.mudak-wrm.kit.edu

Financed by Federal Ministry of Education and Research, BMBF

Acknowledgements and collaboration : Heloise Knapik, Lediane Marcon

Financed in Brazil by : Capes

5.4. Work package 4 – Close range remote sensing

5.4.1. Introduction and objectives

A qualitative and quantitative assessment of the sediment input into reservoirs can be significantly supported by remote sensing methods. Especially in terms of the extensive and regional to global availability, this data can increase the expressiveness by magnitudes compared to in-situ measurements. While satellite remote sensing focuses on a regional scale, this project aims to provide highly detailed close range remote sensing information of water bodies on a local scale. Of particular interest are inflows and their inputs to the reservoir, especially after heavy rainfall events, as well as the distribution of constituents within the reservoir.

For these tasks innovative remote sensing technologies are integrated on a small and flexible Unmanned Arial Vehicle (UAV) which allows for monitoring solutions that can be tailored to the needs of specific applications. This is now possible thanks to the latest generation of robust, compact and lightweight sensors such as hyperspectral cameras and thermal remote sensing sensors. These sensors can be operated on small UAVs and allow the transfer of established methods from air borne and space borne remote sensing to such small and easy to use platforms. While close range remote sensing is already commercially established in precision farming, its application for monitoring of water bodies is not yet well advanced (Gholizadeh 2016).

In this project, close range hyperspectral remote sensing is used to bridge the scale jump between the area-wide large-scale integrating satellite observations and the point wise and sparsely distributed in-situ measurements. At the same time the close range remote sensing is mediating, since it applies the methods of satellite-based remote sensing, but is applied close to the ground and thus below the cloud cover. This is a major advantage over space borne methods which often cannot provide data for weeks due to cloud cover. This issue is illustrated in Figure 49, which shows that the time gap between cloud free (<10%) Sentinel-2 acquisitions is equal or larger than 20 days for more than 40% of the year in the project area. The time period between consecutive cloudless satellite acquisitions is regularly larger than one month, which is unsuitable for a consistent and flexible monitoring approach. In contrast, a close range system can be used even under dense cloud cover and especially immediately after heavy rainfall events when a maximum of organic and inorganic components enters the reservoir. In addition, it also simplifies the important step of atmospheric correction of measured satellite data.

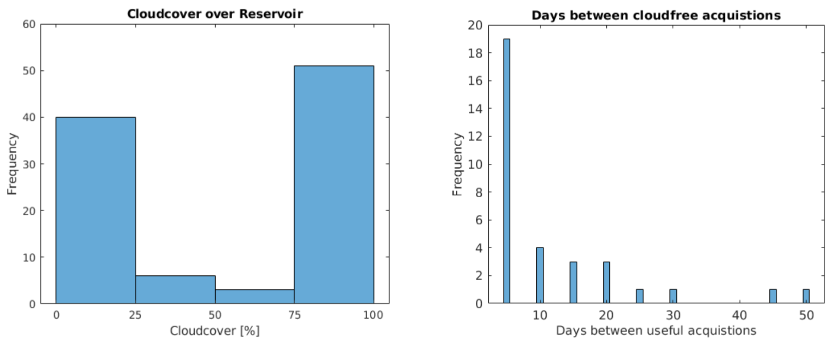


Figure 49 Left: Histogram of Cloudcover. Right: Histogram of time periods between consecutive cloudless (<10%) Sentinel-2 satellite acquisitions at the Passauna reservoir from July 2019 to November 2020 covering 100 scenes.

Water quality parameters which interact with the electromagnetic spectra of the sun are the primary target parameters in this sub-project. These are in particular the total suspended solids concentration (TSS), the chlorophyll-a concentration (chl-a), the colored dissolved organic matter (CDOM), temperature (T) and the turbidity of the water. With regard to an operational and commercial application of the developed methods, this sub-project aims to use UAV-based remote sensing to reduce the labor- and cost-intensive sampling. The overarching objective is the description on an automated and autonomously working minimum monitoring system as a combination of in-situ measurements and remote sensing.

5.4.2. Preparation and method

Plenty of the constituents in natural inland waters interact with the electromagnetic radiation of the sun which is scattered and reflected by the water body and can be detected as water leaving remote sensing reflectance (Ritchie 2003). The optical complexity of the water body due to superimposing effects hampers the estimation of these parameters. Therefore, catchment and seasonal specific optical characteristics can only be captured by sensors with high spectral resolution, i.e. hyperspectral sensors with high signal to noise ratio. Methods like direct inversion, radiative transfer models or machine learning approaches are applied rather than simple band ratio algorithms to obtain reliable estimates for these complex water bodies.

In terms of quantity the most important constituent is suspended solid material (TSS). Another constituent interacting with light is coloured dissolved organic matter (CDOM). It can be used as proxy for other parameters not interacting with light, like the biological and chemical oxygen demand (COD), the dissolved organic carbon (DOC) and the total phosphorous content (TP). Eutrophication and blue algae growths can be detected by the absorption features of photosynthetic active pigments like chlorophyll and phycocyanin.

There are decisive advantages of close range remote sensing over the established remote sensing methods. Data acquisition is flexible in time and space and is adaptable to the local boundary conditions (weather, phenology, agricultural usage, structural changes in the catchment etc.). Also, the spatial resolution is flexible by changing flight height. However, the main argument is, that the biggest part of the particle transport of a catchment takes place immediately after heavy rain events at few days per year (Horowitz 2013). Therefore, an adapted monitoring procedure is necessary that follows the hydrological dynamic better than the established sampling according to a fixed scheme.

5.4.3. Implementation

For a successful implementation of the work package a new imaging sensor system and a UAS needed to be obtained. At the beginning there was no adequate complete system available which addressed the specific demands of the project. Therefore, a system was built up and successively integrated on the platform. The process from system set up to a reliable water quality parameter map is shown in Figure 50.

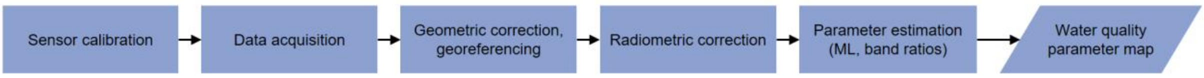


Figure 50: Flowchart from the initially set up of the UAS to the final product of water quality map.

The optical sensors where calibrated using professional calibration tools in a lab at KIT and outdoor measurements. Investigations of the sensor characteristics are published in (Kern 2018). After optimization of the sensor system and calibration of all sensor components, the data acquisition methods were developed to increase the geometric precision and to reduce remaining radiometric artefacts. Finally state of the art methods provide adequate results in terms of water quality parameter maps. The UAV, the integration of the sensor system and the methods for estimation of the desired water quality parameters are presented in the following sections.

Unmanned Aerial System (UAS)

The used UAS is a coaxial octocopter of the company Copter Squad UAS UG which has a maximum payload capacity of 4.5 kg and weighs less than 10 kg when fully equipped. The imaging sensors are attached via a two-axis gimbal to achieve stable viewing angles in nadir direction or any other desired viewing angle (Figure 51). To ensure a precise positioning of the copter, it is equipped with differential RTK-GNSS. In case of a technical failure, the UAS is equipped with self-inflating life jackets to prevent a complete loss if it falls into the water. The maximum flight time with full payload is around 15 minutes with a mapped area of approximately 0.1 km² at flight height of 120 m above ground level and flight velocity of 6 m/s (Kern 2019).

Weight (incl. Sensors)	9.5 kg
Flight time	<15 min
Flight height	120m
Speed	6 m/s

Figure 51: Assembled Unmanned Aerial System (UAS) and its specifications.

Sensor System

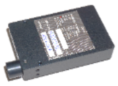
The multi sensor imaging system consists of three cameras and a spectrometer (Table 7). A hyperspectral camera to measure the upwelling radiance of the object combined with an upward looking spectrometer to measure the downwelling irradiance which allows the calculation of reflectance values to estimate water quality parameters like turbidity. A thermal infrared camera is used to map the water surface temperature. Further a RGB camera is integrated for additional optical information.

As hyperspectral camera the lightweight S185 from Cubert GmbH (Ulm, Germany) was chosen. It features snapshot acquisition of hyperspectral images with 125 channels in the wavelength range from 450 nm to 950 nm with a sensor size of 50x50 pixels and therefore fits the requirements for remote sensing of water quality parameters. The innovative snapshot technology can outperform traditional push broom sensors in terms of more flexibility for radiometric correction in post-processing. A second sensor in the camera simultaneously captures a panchromatic image with higher resolution, which is co-registered to the hyperspectral image. The upward looking spectrometer qmini from RGB Photonics GmbH (Kelheim, Germany) captures the downwelling irradiance with 2500 channels in the spectral range from 225 nm to 1000 nm.

The thermal infrared camera Tau 2 from FLIR uses an uncooled micro bolometer sensor with 640x512 pixels which is sensitive in the spectral range from 7.5 to 18.5 µm to measure temperatures at the water surface. The camera weighs 100 g and acquires images with a framerate of up to 25 Hz.

For more visual information about the conditions during the flight and for post processing purposes we use the high resolution Survey3 RGB camera from MAPIR.

Table 7: Summary of all sensors of the UAS and their specific characteristics.

	Hyperspectral Camera	Spectrometer	Infrared Camera	RGB Camera
				
	Cubert FireflEYE (S185)	rgb photonics Qmini	Flir Tau 2	Mapir Survey 2
Wavelength [µm]	0.450 – 0.95	0.225 – 1.0	7.5 – 18.5	-
Channels	125	2500	1	3 (R,G,B; Bayer)
Resolution	8 nm @ 532 nm	1.5 nm	-	-
Sampling [nm]	4	0.31	-	-
Weight [g]	580	60	100	60
Sensorsize [Pixel][Pixel]	50x50 1000x1000 (Pan)	1	640x512	4608x3456
Field of view [°]	33x33	Cosine corrector	45x37	82x60

Calibration

To calculate reliable reflectance values as the ratio of radiance and irradiance - which is measured by different sensors - either a precise absolute calibration or a cross calibration between the sensors is necessary. The calibration process is visualized in Figure 52. It starts by modeling the dark current (DC) which depends on temperature of the sensor array and the integration time. The non-linearity (NL) refers to the sensor specific deviation from a perfect linear behaviour. It can be estimated and modelled for each sensor based on lab measurements with a defined luminance standard. The wavelength calibration (WL) ensures that the correct wavelength is assigned to each channel. Finally, the cross calibration between the sensors can be calculated taking into account the spectral resolution of each sensor. In our case the DC, NL and WL calibration were carried out in a lab using professional equipment and the cross calibration was carried out outdoors using an optimized setup under sunny conditions in combination with a calibration panel with known reflectance characteristics. For the hyperspectral camera further geometric and radiometric effects need to be corrected due to the lens system.

Figure 52: Flowchart of calibration for optical sensors.

Data Acquisition

During our filed campaigns we improved the system itself and the way of data acquisition continuously. In the following, the optimised set up is briefly described. The flight height is set to 120m and the optimum speed to 6 m/s which is a trade-off between the spatial resolution, the mapping progress and motion blur of the captured images. All sensors acquire data in individual continuous streams. The hyperspectral camera and RGB camera are set to 2 Hz frame. The thermal camera acquires images with around 27Hz. The frame rate of the irradiance spectrometer is dependent on the integration time, but generally has a higher frame rate than the other sensors. There are three different time references for the thermal camera, RGB camera and the hyperspectral sensors. The synchronisation of the data is done manually.

Mosaicking

In general, it is assumed, that all cameras are nadir looking. Therefore, the mapping of the flat water surface is reduced to a simple scaling factor and the coordinates of the image centre.

Due to inaccuracy of the navigation information, the time synchronization and a remaining small movement of the gimbal the resulting maps show initial location errors up to 10m. In case of stable features in the images, like points on the shore, computer vision algorithms can be used to increase the mosaicking accuracy. We optimized the mosaicking process using an automatic least squares adjustment in cases when the images include sufficient stable features.

Radiometric Correction

Hyperspectral Data

The simultaneously measured irradiance allows a radiometric correction of effects caused by changing illumination. Non-water pixels can easily be detected and removed using the normalized difference water index (NDWI). Spectra showing effects of reflected sunlight or sky radiance at the water surface can be partly detected and removed. Methods under development will allow the detection and reduction of sun and sky glint on the spectra. During the flight, points are repeatedly observed from different viewing angles and under different cloud conditions. By applying simple statistics like median filtering in a final step, the high redundancy of observed spectra along the flight path can be used to reduce remaining artefacts from sun glint and sky glint from the water leaving reflectance signal.

Thermal Data

All datasets show changing sensor characteristics of the thermal camera during the flights, which cannot be compensated by calibrated in a laboratory. There are two major effects: First a temperature drift which affects the read out of the complete sensor array and second a variable “vignette” which is visible as cold edges resulting in varying temperature values which are not representing the real temperature values in the scene. The temperature drift can be corrected by assuming, that consecutive images have the same median temperature value. The variable vignette is calculated using images which show only water surface which is checked for homogeneity. Due to the described effects, it is inevitable to measure ground truth temperature data for validation and offset correction.

Parameter Estimation

The estimation of water quality parameters like TSS with hyperspectral images relies on the water leaving reflectance. This is, in simplified terms, the ratio of downwelling irradiance (sky and sun) and upwelling radiance of the waterbody which is mainly reflected and scattered by the water. Our system provides the ability to measure the irradiance during the flight to account for changing illumination conditions. A well-established method for parameter retrieval from multispectral data are fine-tuned band ratio algorithms using individual bands from hyperspectral data sets. To make use of all information that is contained in the hyperspectral data, another option is to use more sophisticated radiative transfer models which need a specific expert knowledge of operator. For specific applications the use of state-of-the-art machine learning methods can be advantageous over before mentioned methods. However, these methods need a certain minimum number of measured spectra along with ground truth values of the desired parameters to be applied. A common machine learning method for spectral analysis is the partial least squares regression (PLS) (Wold 2001). In the last years there have been several studies on using further machine learning tools such as neural networks which show promising results also by combining observed and simulated data (Keller 2018; Maier 2019).

Figure 53 shows the scheme of our process using PLS as a machine learning method for water quality parameter estimation. In a first step, the so-called model training, spectral measurements are combined with ground truth parameter values from water samples and in-situ sensors and if possible, further simulated data. In this phase the available data is split into sub datasets. Usually, it is divided into three sets, training, testing and validation data. Training and validation data is used to optimize the model. The tuned model is then tested using the test subset. In case of only few available ground truth data, a cross validation approach is used. In a final step the model is trained with the optimized settings and all data. The trained model can then be used for parameter estimation. The input data are hyperspectral images and the output are pixel wise estimated water quality parameters which need to be mosaicked to get the maps.

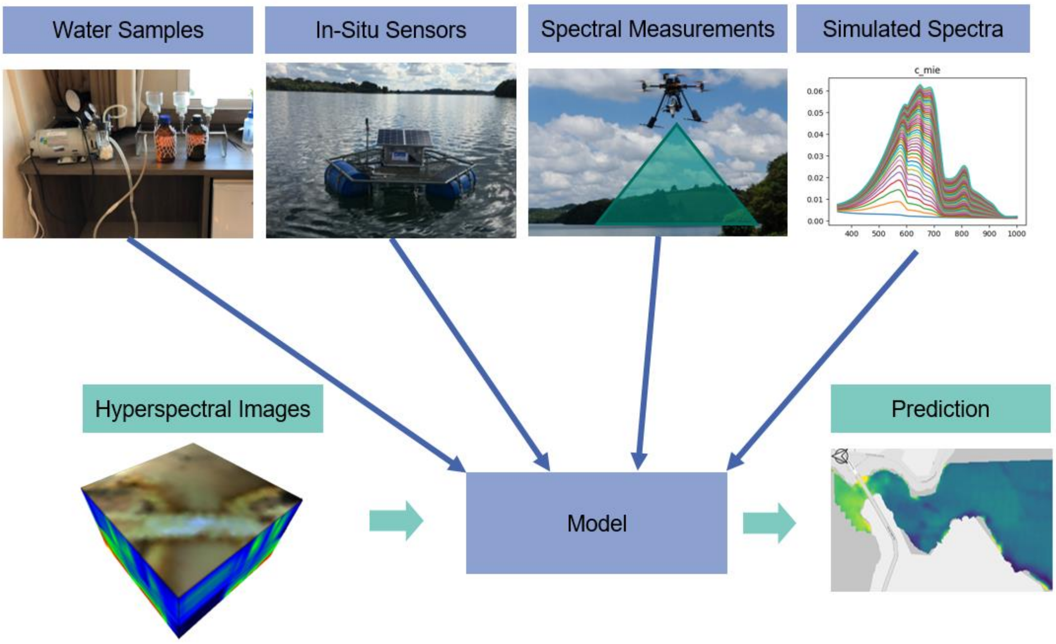


Figure 53: Scheme of training and using a machine learning model. The upper row shows the data necessary to train the model. Spectral measurements and simulated spectra are combined with results from analyzed water samples and in-situ measurements. The lower row represents the application of the model to hyperspectral images which enables the estimation of the parameter in question.

Field Campaigns

During field campaigns in the years from 2017 to 2020 we acquired various datasets. Starting in 2017 first studies using close range remote sensing have been conducted by a boat-based approach. This set up allowed to acquire hyperspectral data in an automated way with high frequency measurements along the trajectory of a boat during in-situ and water sampling campaigns along the reservoir. From 2018 onwards, UAS based datasets were acquired of areas of interest. Especially the northern part, the main inflow, was used as a study site. This area is easily accessible by car and boat and it is expected to show the highest gradients of water quality parameters like temperature and TSS concentration. Due to hardware defects, not all datasets acquired with the UAS provide hyperspectral images. A brief summary of the acquired data is given in Figure 54.

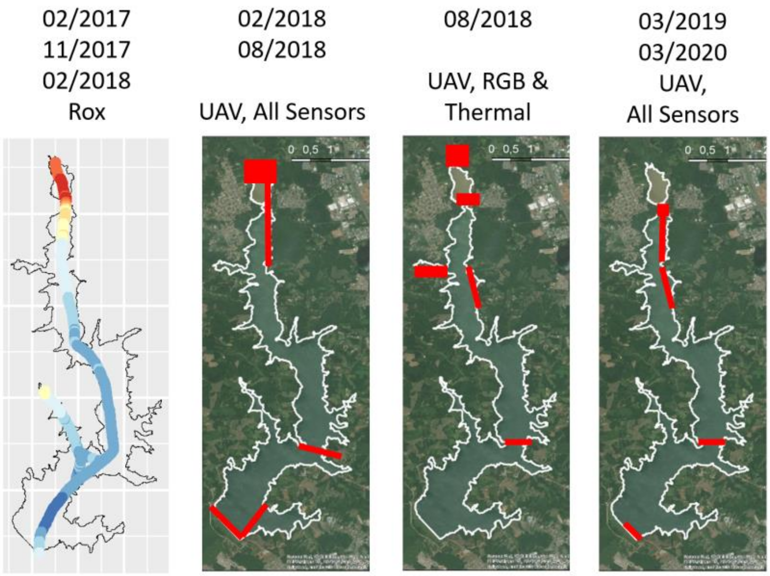


Figure 54: Summary of the data acquired at the Passauna reservoir. During the first three measurement campaigns we focused on method development using a boat-based setup. Starting in February 2018 we acquired data with the UAS based sensor system over different areas of interest, with main focus on the northern part, the intake area and the dam in the south.

5.4.4. Results

Calibration

The spectral sensors, the hyperspectral camera and the irradiance spectrometer have been calibrated in a combined approach using professional lab equipment and low-cost outdoor measurements. The spectrometer was fully characterised in terms of DC and NL modeling and wavelength calibration. The hyperspectral camera doesn't provide an internal temperature sensor. Therefore, the DC was investigated and in case of not available DC measurements in the field a constant value of 2 DN is assumed. NL modeling was possible for the hyperspectral camera. The major part of nonlinearity was removed, but some nonlinear effects remain especially at very low and very high spectral bands. The wavelength calibration of the camera was performed pixel wise and takes into account the increasing spectral resolution from short to long wavelengths. The light fall off caused by the lens system of the camera and further inhomogeneities where investigated and modelled using lab measurements of a luminance standard.

The use of an irradiance spectrometer, with our setup, outperforms the common use of a reference target with known reflectance characteristics in the field. Figure 55 demonstrates the conventional measurement setup of such a reference panel on the left image and the pixel wise mean reflectance of the measured reference panel of one hyperspectral image on the right. In this case the reflectance is calculated using one measurement of the irradiance spectrometer as reference. The reflectance panel has an average reflectance of 51%, but with this approach it is obvious, that the acquired image shows a drift of more than 6 %.

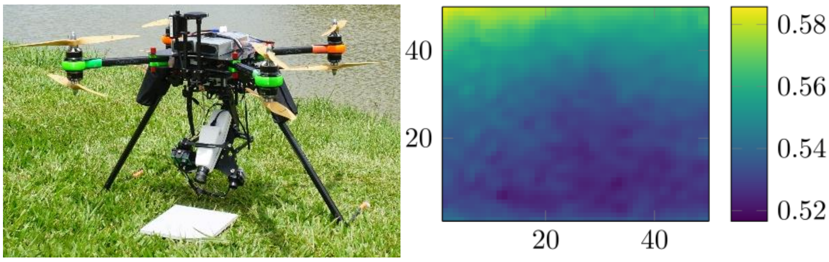


Figure 55 Left: Setup to measure the reflectance reference panel. Right: Mean reflectance of the acquired hyperspectral cube calculated by using the measurement of the irradiance spectrometer as reference. It is clearly visible, that the measurement is falsified by a systematic drift across the image.

Groundtruth Measurements

The analysis of the groundtruth measurements taken in the field campaign in 2020 show high correlation of turbidity measured with in-situ sensors and TSS concentration of water samples analysed in a laboratory (Figure 56). The turbidity measurements show an average standard deviation of 5% of the measured value. Due to low chl-a concentrations of less than 20µg/l the accuracy of the in-situ sensor could not be investigated and therefore a reliable estimation is not possible with this data. Total phosphorus is highly correlated to TSS concentrations. Thus, it is possible to infer TP concentration using the TSS estimations (Wagner 2019). Indeed, this correlation needs to be validated on a regular basis.

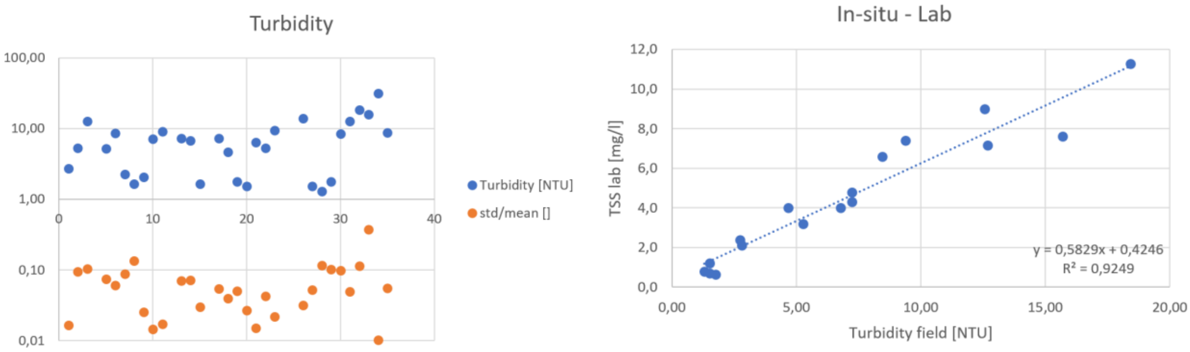


Figure 56: Mean turbidity readings and standard deviation for several in-situ observation points during field campaign in 2020 (left). In-situ turbidity measurements and TSS concentrations from lab analysis show a reasonable correlation (right).

Boat-based Measurements - RoX

As the setup and calibration phase of the UAV sensor system took more time than initially planned, a boat based close range remote sensing approach was conducted in preliminary studies to test the instruments and methods. The results of these campaigns are presented in (Wagner 2019). The studies used a 'ROX' instrument (JB Hyperspectral Devices, Düsseldorf) to measure the reflectance of the reservoir. The device is based on a FLAME-S-VIS spectrometer (Ocean Optics, Dunedin FL, USA). The two ends of a bifurcated glass fibre leave the spectrometer point at the nadir and zenith, respectively. The downward-looking fibre measures upwelling radiance within an opening angle of about 20°. Shutters alternately close one or both fibres to measure up-welling radiance, downwelling irradiance and the dark current in each measuring cycle. After subtracting the dark current, reflectance is calculated as the ratio between downwelling irradiance and upwelling radiance. We mounted the spectrometer to a boom stand on a small motor boat (Figure 57). From about 1.2 m above the water surface, the sensor pointed at the water surface out-side the boat shadow and measured reflectance spectra in short time intervals of about 10 seconds, while we drove transects across the impoundment. This way, we recorded water surface reflectance spectra from 400 to 900 nm with corresponding location and time information. The preprocessing includes smoothing using a Savitzky-Golay filter, normalization of the spectra and calculating the first derivative. The parameter estimation was performed by PLS regression. The spectra were split in training and test sets and a cross validation approach was used to train and evaluate the model.

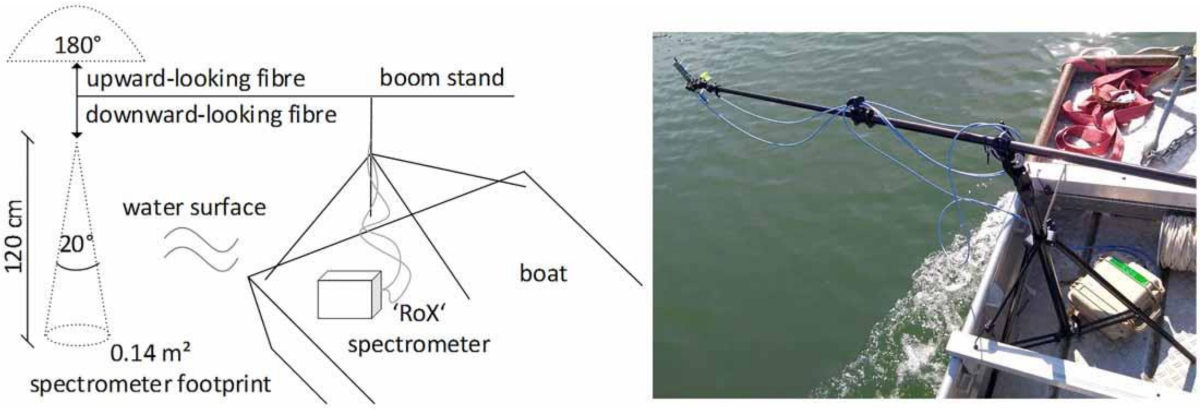
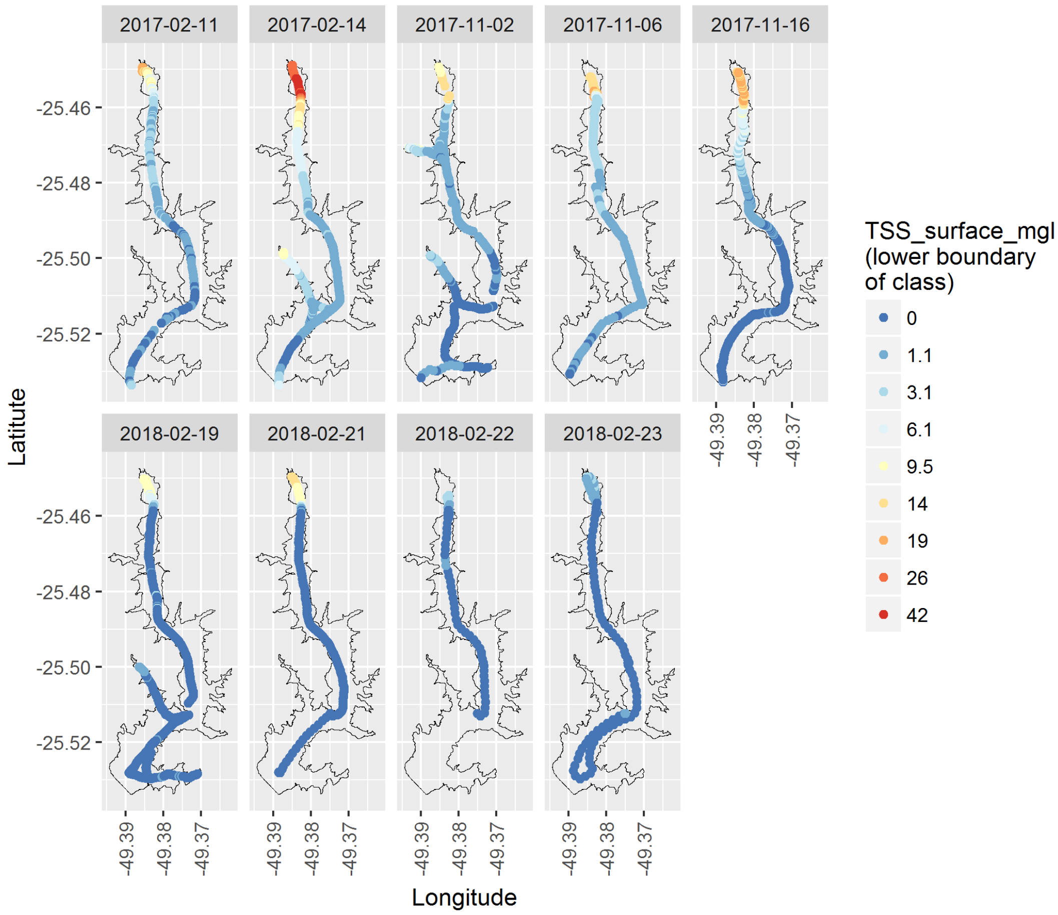
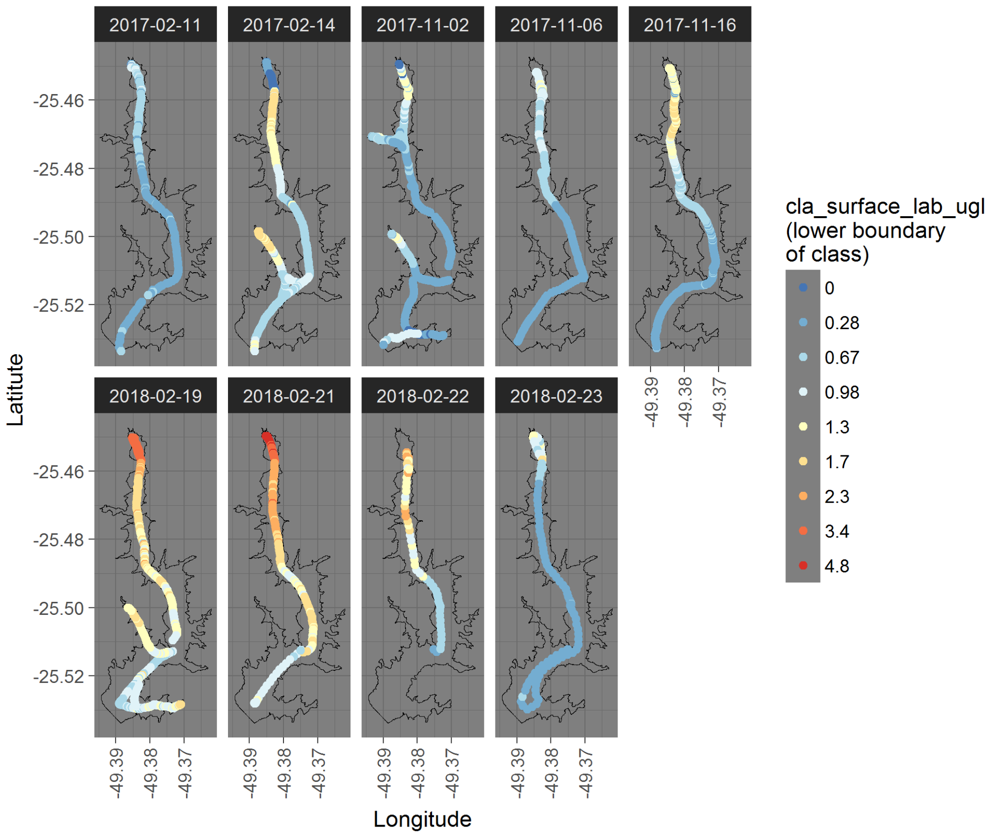


Figure 57 Left: Scheme of the boat setup used to acquire reflectance measurements at Passauna drinking water reservoir. Right: Photograph of the system during measurement.

The results of boat-based measurements of the campaigns in 2017 and 2018 are shown in Figure 58. Water sampling for lab analysis and in-situ measurements were taken at various locations which show different water quality characteristics. These ground truth measurements were used to train the model.





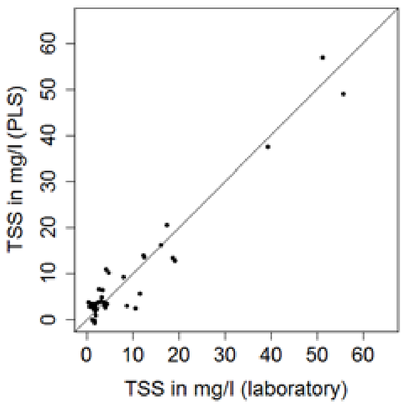


Figure 58: Water quality maps. Parameters are estimated from boat-based hyperspectral close range observations during measurement campaigns in 2017 and 2018.

Water quality parameter maps

Turbidity

Our acquired ground truth dataset does not provide enough data points to apply advanced machine learning models in a common approach. We therefore use the formerly described method of partial least squares (PLS) in combination with cross validation to estimate turbidity from hyperspectral data. The model using cross validation for training and evaluation provides results with a mean average error (MAE) of 3.26 NTU. The training of the model with all data points and evaluation with the same provides an MAE of 1.39 NTU. By using the results of analysed water samples at the same points, it is possible to convert these turbidity measurements to TSS concentrations.

Using above described post processing methods, the generated maps show good results with only little remaining artefacts caused by cloud shadows and sun and sky glint (see Figure 59 and Figure 60).

Temperature

The raw images of the thermal infrared camera show sensor characteristics which change over time and a temperature drift. After correction of these effects and correction of the absolute temperature offset, the results show that the accuracy of the temperature maps is less than one degree Celsius. It must be noted that the reference surface temperature measurements should be taken synchronously while data acquisition with the UAS.

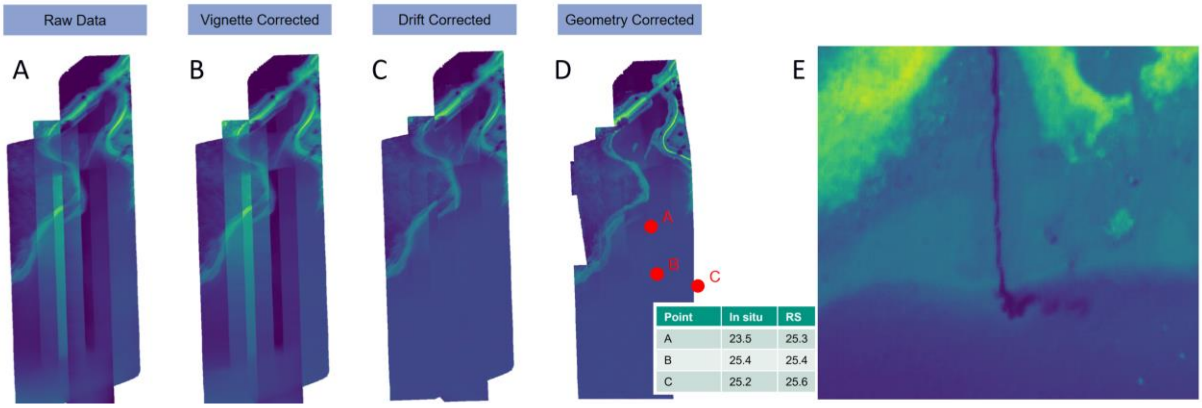


Figure 59: Example of water surface temperature from UAV observations. A-D show the processing steps from raw acquisitions to the final corrected and geocoded map. E shows a single image of this data set with inflow of colder water into the reservoir.

Postprocessing Software

Within the project a prototype software was developed to interactively run the whole processing chain for the acquired hyperspectral data. A screenshot of the user interface is shown in Figure 60. The software allows the user to visualize the acquired raw data as images and spectral values. The processing tools allow to change basic settings. Intermediate results show the different processing steps to choose the proper parameter settings and check for plausibility. Finally the map with the desired parameter is generated and visualized.

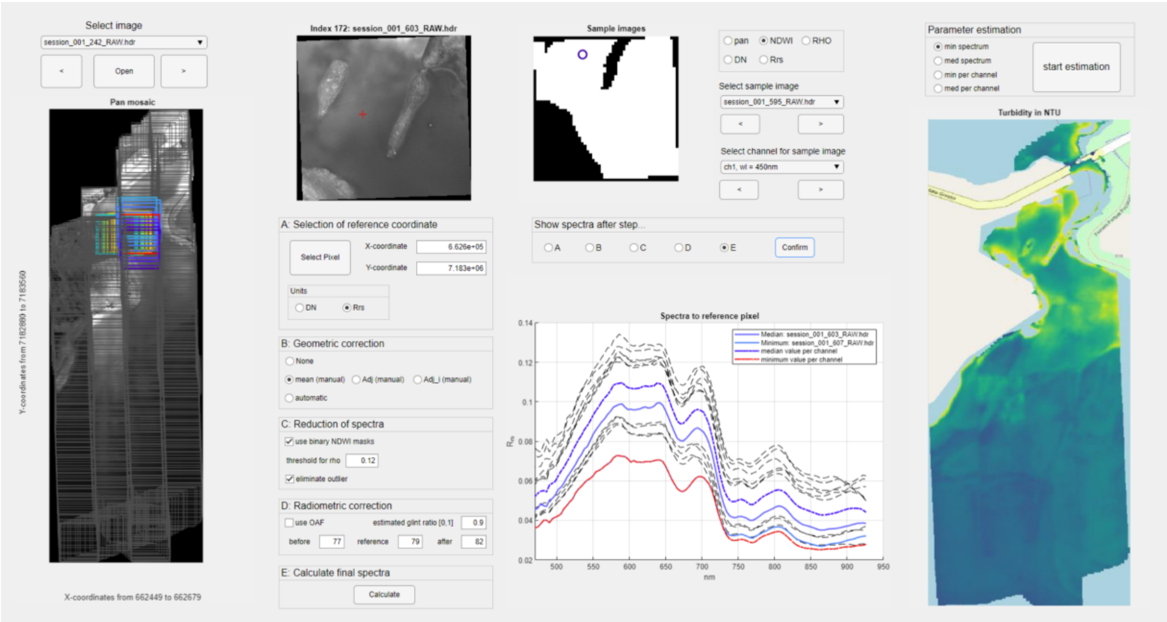


Figure 60: Screenshot of the developed application for postprocessing hyperspectral data and estimation of water quality parameters.

Cross validation with Satellite Remote Sensing

The field campaign in early 2020 was synchronized with the Sentinel-2 acquisition schedule to allow the comparison of hyperspectral close-range data with multispectral data from Sentinel 2A, complemented with in-situ measurements and water samples. The groundtruth measurements have been taken at different locations of the reservoir to cover a wide variation of target parameters. The graph in the upper right of Figure 61 shows estimated suspended matter concentration from multispectral satellite data against the results of lab analysis. The estimated linear fit is than used to calculate TSS concentrations which can be compared to TSS estimates from hyperspectral UAS data of the same day. The map in Figure 61 shows the overlay of the satellite data with the UAS data (red box) acquired at March 10, 2020. The visual impression, that the estimated TSS concentration using these two methods fit to each other, can be verified with the histogram of residuals between both methods (lower right of Figure 61). The cross validation shows a standard deviation of 1.6 mg/l and a systematic deviation of 0.8 mg/l. Other datasets of the same day confirm these results.

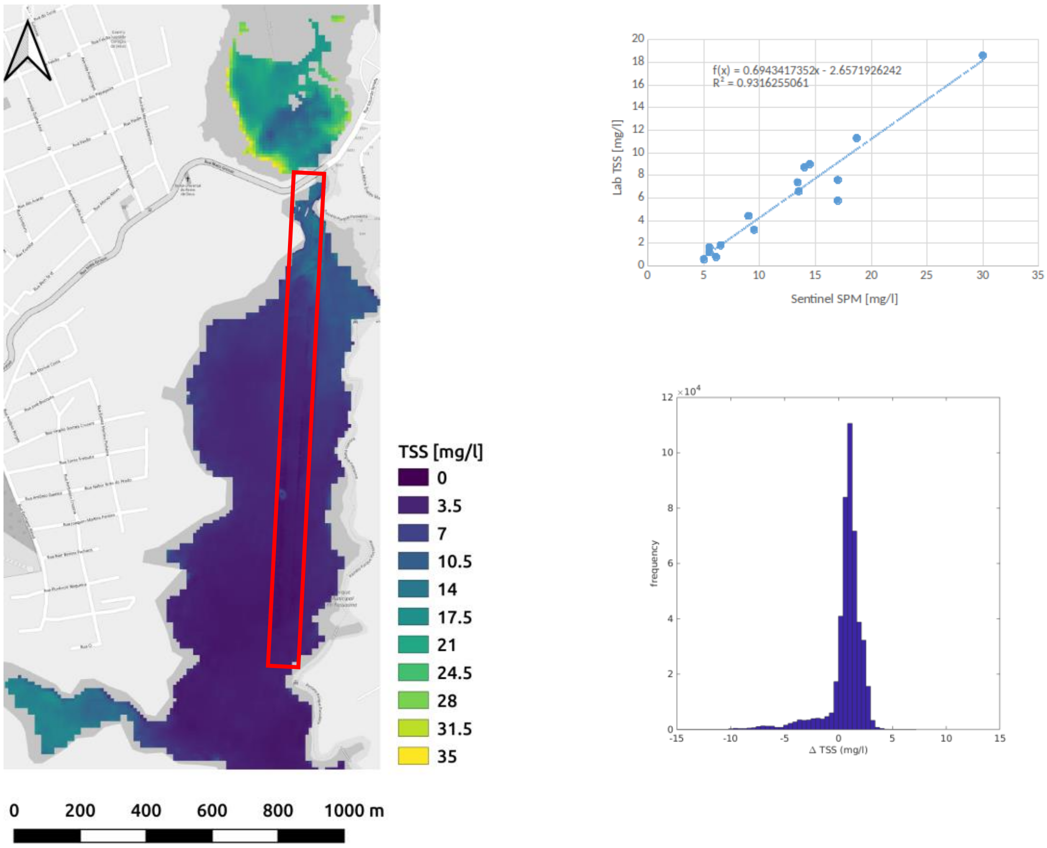


Figure 61 Left: Map of total suspended solids (TSS) estimated from hyperspectral UAS-based close range measurements and overlay of TSS estimates from multispectral satellite-bases remote sensing (red box). The graphs on the right show the scatterplot of both estimates (top) and histogram of residuals (bottom).

Lessons Learned

Based on our experience and the developed prototype, we want to give some recommendations for data acquisition of hyperspectral images and its processing. Images should be acquired as a continuous stream with as much overlap in flight direction and between flight lines as possible. A high redundancy enables an optimized and precise parameter estimation. To ensure a mosaicking with high geometrical quality it is inevitable to know the exact pose of every image taken by the different sensors. Therefore, we recommend a sensor system where all sensors are coupled to a common time reference or use the data stream of the flight controller of the UAS. For productive use, we recommend to consider the use of a fixed wing UAS which is able to start and land vertically. These systems can also start and land on difficult terrain but have a significantly longer flight time (more than one hour) and therefore map much larger areas as the system used in this project. However, these systems are limited by a minimum flight speed, which needs to be considered against the flight height and respective acquisition parameters (pixel resolution and integration time) to avoid image blurring with increased speed.

Contribution towards a Minimum Monitoring Concept

As a minimum monitoring concept, we recommend a lake specific estimation model which should be trained using spectral data and ground truth data in a wide range of occurring parameters. The model could then be validated annually or biannually or in case of significant changes e.g. in the catchment of the reservoir. The use of the system is especially recommended if there are algal blooms expected or if satellite remote sensing is not possible over a long period of time. For reservoirs that are highly susceptible to heavy rain events, a UAS based reservoir mapping can be a valuable contribution to the monitoring concept. With the expected automation in UAS systems, a fully autonomous sensor system would be feasible.

Ground based hyperspectral measurements can be used at points of interest providing continuously measured data. A use case of such observations is the monitoring of rivers to get continuous data at daytime.

In-situ sensors should be used for precise measurements at points of interest for continuous or campaign-based data acquisition. To prevent erroneous measurements due to biofilm on the sensors an advanced setup is necessary. Especially for measurements in variable depths the use of in-situ sensors and/or traditional water sampling is mandatory for a holistic monitoring concept.

Future Research

Even if we have developed a fully operational system, there is potential for further optimization. The developed methods for reduction of sun and sky glint provide good results. Still some artefacts are still visible on the produced water quality parameter maps. To further optimize these procedures a second camera taking images of the sky could provide the necessary data to correct especially reflected clouds on the water surface.

The comparison of data acquired with the hyperspectral camera and satellite-based observations show consistent results. This enables further innovative approaches to build easy to use methods for training machine learning models using only few in-situ measurements and water samples.

References of WP4:

Gholizadeh, M. H., Melesse, A. M., & Reddi, L. (2016). A comprehensive review on water quality parameters estimation using remote sensing techniques. Sensors, 16(8), 1298.

Horowitz, A. J. (2013). A review of selected inorganic surface water quality-monitoring practices: are we really measuring what we think, and if so, are we doing it right?. Environmental science & technology, 47(6), 2471-2486.

Kern, J., Schenk, A., & Hinz, S. (2018). Radiometric Calibration of a UAV-Mounted Hyperspectral Snapshot Camera with Focus on Uniform Spectral Sampling. In 2018 9th Workshop on Hyperspectral Image and Signal Processing: Evolution in Remote Sensing (WHISPERS) (pp. 1-5). IEEE.

Kern, J., & Schenk, A. (2019). A MULTI-MODAL SYSTEM FOR MONITORING OF WATER QUALITY–SETUP AND FIRST RESULTS FROM PASSAUNA RESERVOIR. In Anais do XIX Simósio Brasileiro de Sensoriamento Remoto (SBSR), (pp. 3157-3160). INPE.

Maier, P. M., & Keller, S. (2019). Application of different simulated spectral data and machine learning to estimate the chlorophyll a concentration of several inland waters. In 2019 10th Workshop on Hyperspectral Imaging and Signal Processing: Evolution in Remote Sensing (WHISPERS) (pp. 1-5). IEEE.

Keller, S., Maier, P. M., Riese, F. M., Norra, S., Holbach, A., Börsig, N., ... & Hinz, S. (2018). Hyperspectral data and machine learning for estimating CDOM, chlorophyll a, diatoms, green algae and turbidity. International journal of environmental research and public health, 15(9), 1881.

Knaeps, E., Sterckx, S., & Raymaekers, D. (2010). A seasonally robust empirical algorithm to retrieve suspended sediment concentrations in the Scheldt River. Remote Sensing, 2(9), 2040-2059.

Olmanson, L. G., Brezonik, P. L., & Bauer, M. E. (2013). Airborne hyperspectral remote sensing to assess spatial distribution of water quality characteristics in large rivers: The Mississippi River and its tributaries in Minnesota. Remote Sensing of Environment, 130, 254-265.

Ritchie, J. C., Zimba, P. V., & Everitt, J. H. (2003). Remote sensing techniques to assess water quality. Photogrammetric Engineering & Remote Sensing, 69(6), 695-704.

Wagner, A., Hilgert, S., Kattenborn, T., & Fuchs, S. (2019). Proximal VIS-NIR spectrometry to retrieve substance concentrations in surface waters using partial least squares modeling. *Water Supply*, *19*(4), 1204-1211.

Wold, S., Sjöström, M., & Eriksson, L. (2001). PLS-regression: a basic tool of chemometrics. Chemometrics and intelligent laboratory systems, 58(2), 109-130.

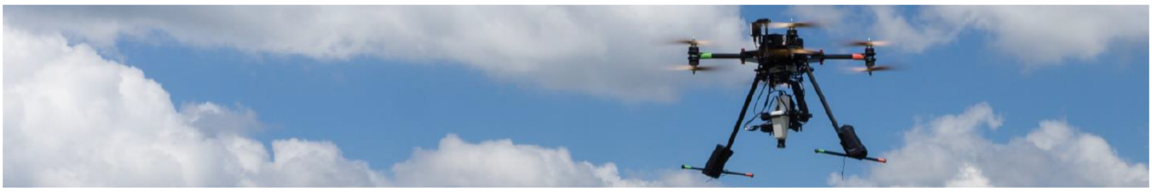
5.4.5. Flyer

MuDak-WRM

FONA Research for Sustainable Development BMBF

Sponsored by the Federal Ministry of Education and Research

UAS system to ensure continuous monitoring of basic water parameters in the reservoir



Context

The amount and spatial distribution of key parameters in reservoirs like suspended solids, chlorophyll and the temperature at the water surface can be assessed by multispectral and hyperspectral remote sensing. This kind of reservoir monitoring is low-cost, continuous and provides full spatial coverage with high resolution. It provides valuable information for modellers to set-up boundary conditions and assimilate models and it can be supportive to optimize the water sampling and avoiding biased sampling.

State of the art techniques are based on space-borne multispectral data which produces reliable results, but provides no or only limited information during and after rain events when the major sediment input occurs. Statistics for Sentinel-2 at the Passaúna reservoir show that approximately two third of the year, the time gap between cloud free satellite acquisitions is equal or larger than 20 days. This is where the UAS based remote sensing system jumps in to ensure a continuous monitoring, in particular during the rainy season.

Objectives

- ✓ A remote sensing system with state of the art monitoring of optical active water quality parameters like total suspended solids, turbidity, chlorophyll and surface water temperature.
- ✓ To ensure continuous remote sensing of surface water quality parameters, independent of cloud coverage.
- ✓ Provision of a remote sensing monitoring system with flexible timing in case of special needs.

Equipment and Method

The UAS is equipped with a multi sensor imaging system consisting of three cameras:

- Hyperspectral snapshot camera (Cubert GmbH, 125 channels, 450 nm – 950 nm) combined with a spectrometer for irradiance control
- Thermal camera (FLIR)
- RGB camera (MAPIR)

The processed data of the hyperspectral camera, shows estimates of water quality parameters like suspended solids and chl-a not only at a single point, but in a spatially extended area. The thermal infrared camera is able to capture the thermal radiation and therefore allows to retrieve images of the temperature of the water surface. All sensors are mounted on a multicopter with up to 15 min flight time, which equals a spatial coverage of 0.15 km². The system provides differential GNSS positioning for each image acquisition point in order to generate mosaicked maps of the respective water quality parameters in a high spatial resolution and with an accuracy comparable to in-situ sensors.

Methodology

The hyperspectral camera and the spectrometer are pre-calibrated in a lab. Variable cloudiness and changing conditions during the flight and between segment flights are handled by calculation of corrected reflectance values using a reference panel in field and the spectrometer measuring the incoming light during the flight. Further processing accounts for sun-glint and geometric distortions like pitching of the copter in windy situations. Following, the desired target parameters are estimated by choosing from different state of the art machine learning regression algorithms like partial least square (PLS) and artificial neural networks (ANN). Finally, individual images are mosaicked to parameter maps using the pose information of the copter and further processing.

The whole workflow is implemented in a fast processing pipeline, which is accessible through a user interface (see Figure 1). In an intuitive way the software shows the mosaic of the pan images with individual boundary boxes. Single images can be chosen for a detailed analysis of the spectra of individual points in the scene. After choosing the data pre-processing steps, the software generates the desired parameter map.

Innovation and Outlook

- ✓ The UAS monitoring system provides intuitive maps of water quality parameters with high spatial resolution independent of cloud cover.
- ✓ Parameter estimation from full contiguous reflectance spectra are advantageous to multispectral optical acquisitions.
- ➢ For reservoir scale applications and larger areas, a fixed-wing UAS with a comparable sensor system is recommended. An autonomous vertical take-off and landing copter (VTOL) can be used to accomplish fully autonomous close range monitoring.

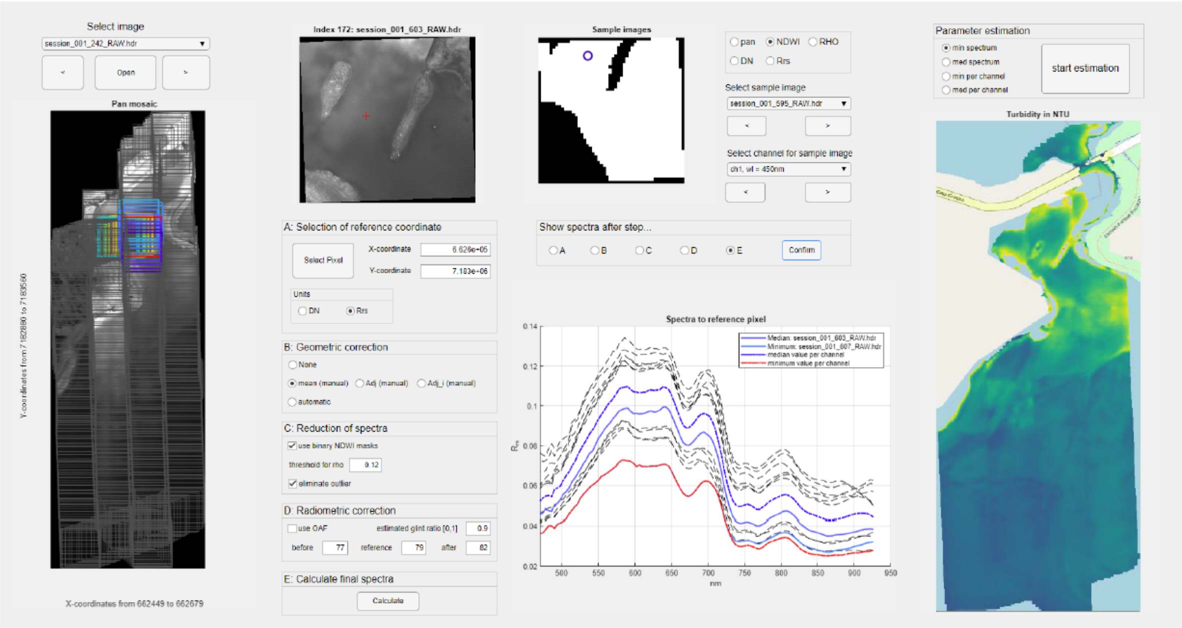


Figure 1 Our user interface shows the analysis and processing of the acquired data of a case study at Passaúna reservoir close to Curitiba, Brazil. The left figure displays a mosaic of the pan images with individual bounding boxes. Selected reflectance spectra are shown in the lower figure. Extensive options allow the user to choose the appropriate settings e.g. for geometric and radiometric corrections. The right figure shows a processed turbidity map.

Authors Jens Kern, Fabian Lorenz, Andreas Schenk and Stefan Hinz

Contact jens.kern@kit.edu

Date 08.10.2020

Web www.mudak-wrm.kit.edu

Funded by Federal Ministry of Education and Research, BMBF

5.5. Work package 5 – Satellite based remote sensing

5.5.1. Introduction and objectives

The quantitative estimation of the terrestrial material discharge potentials can be decisively improved by satellite-based recording of the catchment areas of the artificial lakes. The vegetation cover, dynamics and vitality of agricultural and forestry surfaces as well as different soil characteristics can be represented by satellite image data. Besides the vegetation, sealed areas, open ground and others are determined, so that direct conclusions can be drawn about the degree of total vegetation coverage. This information can then be used as a basis for the material discharge modeling.

The motivation is to find out which of the works and models within the other working packages can be supported, calibrated or verified by using remote sensing methods and remote sensing data. Which remote sensing data and remote sensing products are necessary for that? The scientific objective was to find out which boundary conditions depending resolution, range of values and accuracy for the remote sensing results are necessary to fulfil the demands of the works of the other working packages. And at the end an important question to answer is the improvement reached by using the remote sensing methods compared to the methods used so far.

As in MuDak-WRM the aim is to develop methods and models which are transferable to countries with different levels of development one key point in this project is to consider the transferability of methods and models during the developments. To fulfil this the plan in this project was to start the development of the methods in a test area in Germany and then to transfer them to a test area in Brazil.

5.5.2. Preparation and method

One aim of this project is to develop methods which can be used nearly all over the world in different countries with different stages of development. To fulfil this aim, suitable satellite systems have to be selected which are available all over the world in comparable frequencies. One such system is the European Union's Earth observation programme Copernicus, which contains several satellites called Sentinel. The different Sentinel satellites cover nearly the whole world. An additional benefit is that the images are free of charge and openly accessible to users. Therefore, the system is suitable to be used within MuDak-WRM. Among the different Sentinel satellites two of them can be used for the project purposes: Sentinel-1 and Sentinel-2. Sentinel-1 has a radar sensor, while Sentinel-2 records optical images. Both, Sentinel-1 and Sentinel-2 consist of 2 satellites and have a revisit time of 5-6 days. Sentinel-1 has a resolution up to 5m, Sentinel-2 up to 10m. The characteristic of an optical sensor (like Sentinel-2) is that it is dependent from clouds. If the investigation area is covered by clouds the images cannot be used. Here the radar sensors have advantages: They are independent of clouds.

The approach in this WP5 was first to do a requirement analysis together with the project partner (WP5.1) and to find out which products with which specifications were needed to be used for the different purposes. Based on this analysis a concept for the remote sensing methods and the interfaces was created (WP 5.2 and WP 5.3) and the methods and interfaces were developed (WP5.4, WP 5.5) and tested together with the partners, first in the test area in Germany and (WP 5.6). Based on those results of the tests the methods were improved and extended (WP 5.7). In a second step the methods were transferred to the second test area in Brazil and validated there also (WP 5.8). Based on that validation additional modifications and adaptations were done.

Method Explanation and results

As described above together with the project partners the methods to be developed and the requirements were discussed at the beginning phase of the project. Based on that several methods were developed. In the following the different methods and some results are described:

Land Cover Classification

The land cover classification is one of the most important products derived from remote sensing data in this project. It consists of an assignment of all satellite image pixels to particular classes. That means that the spectral signature of every pixel in the images will become a particular class. As the land cover classification is an input for different other models, simultaneous or methods within the other WPs, the first step of the method development was to decide which classes should be discriminated. After several discussions with the project partners the following list of classes was created, also taking into account the method should be able to be transferred to other regions in the world:

- Urban area
- Informal urban area
- Cropland
- Pasture/meadow
- Bare soil
- Forest
- Scrubland/grassland
- Water
- Wetland

The method used for the land cover classification was a supervised multispectral multitemporal classification. As remote sensing sensor for this purpose as described above Sentinel-2 images were used with a ground pixel size of up to 10m. The satellites revisit time of the same area was 5 days. For a supervised classification reference data were needed for all the determined classes in the images which should be used for this purpose. Using the reference data, the classificator learns which spectral and temporal signatures the particular classes have (model induction) and is later able to classify the other pixels of the images in the same way (prediction).

The selection of the reference data was done manually by people who are familiar with the test area for all classes. In addition, the reference areas had to be selected evenly over the whole area to select the different kinds of appearances in every class. Based on experiences, as an estimation for every class ca. 20.000 pixels had to be selected, that means ca. 2 km^2.

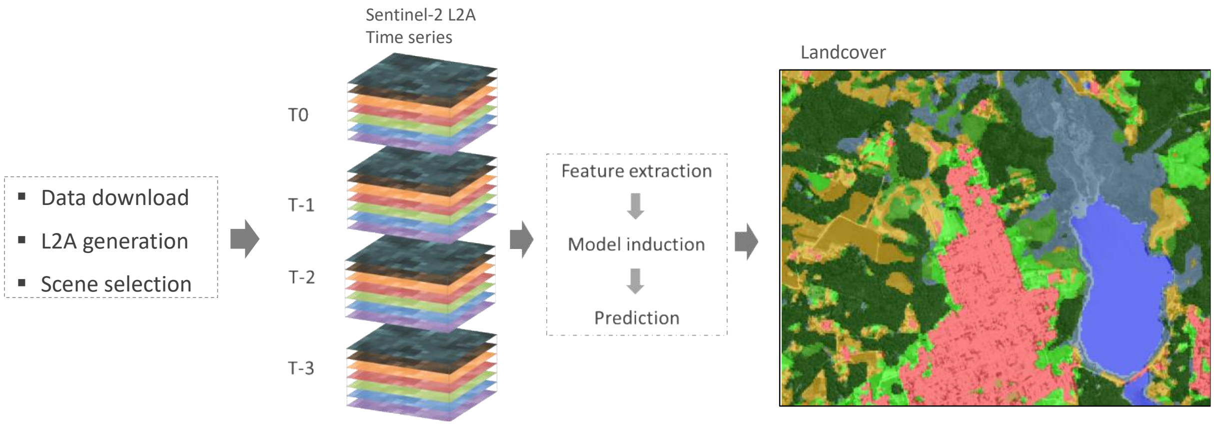


Figure 62: Method of land cover classification.

The supervised classification algorithm used in MuDak-WRM was Random Forest, based on (Breiman, 2001), extended and adapted to the requirements of this project. The distinction between the both classes urban area and informal urban area using only Sentinel-2 images is very difficult and not possible to do in the required quality. Because of that they were fused to one class. As depicted in Figure 62 as input a time series of Sentinel-2 Level 2A images from one year were used to extract the bands as features, to train the classifier (model induction) and to classify (prediction).

The result of the land cover classification for the test area in Brazil, for the Passauna catchment area, using images in 2018, can be seen in Figure 63.

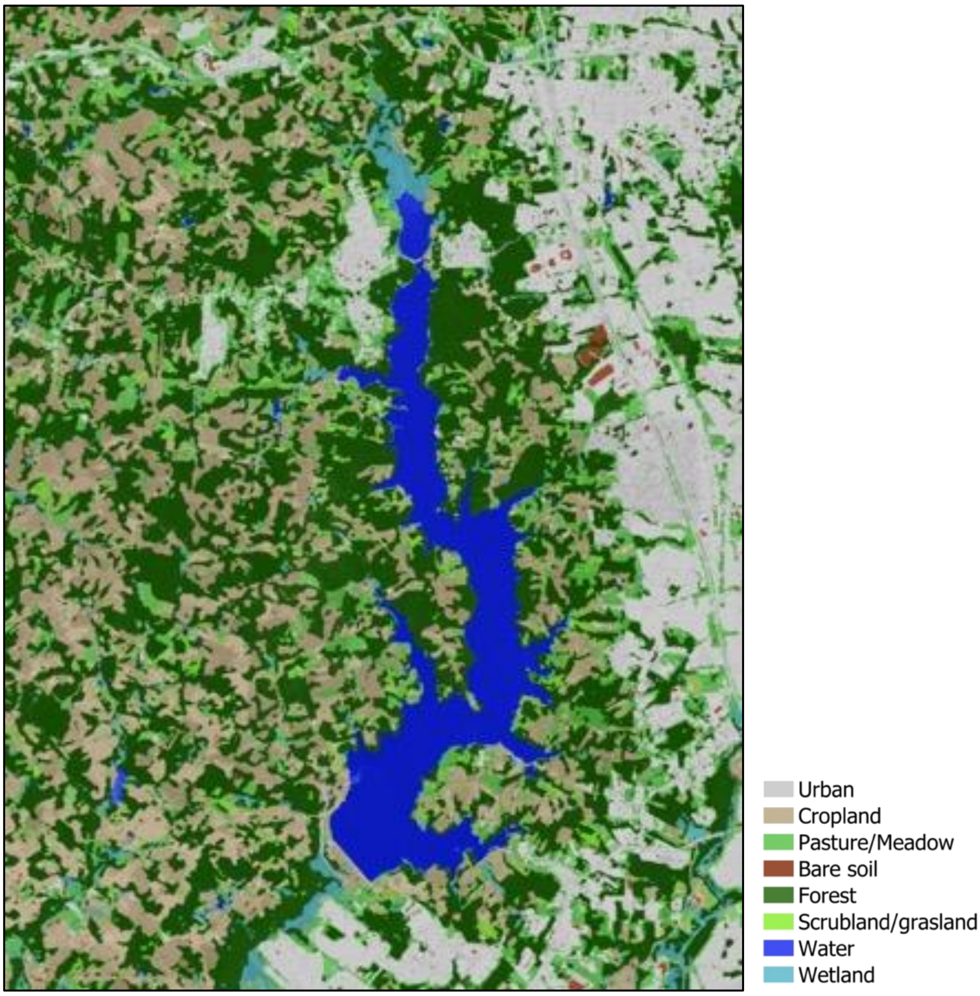
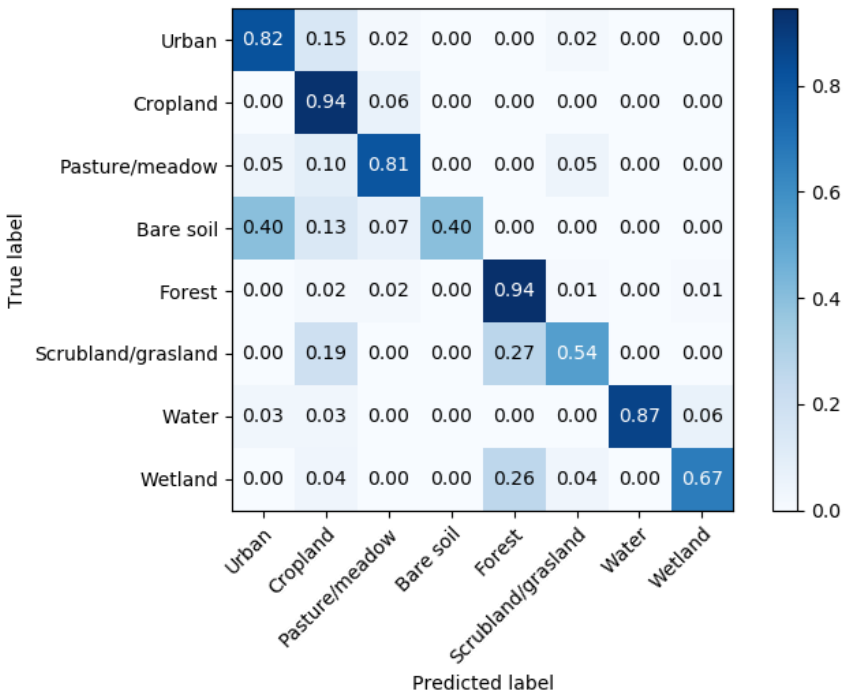


Figure 63: Result of Land Cover Classification, Passaúna area 2018

The accuracy estimation of this classification is depicted in Figure 64. As shown the overall accuracy over all classes is 84%. The classes with worse classification results were bare soil and scrubland/grassland. This is a hint that the reference area of these classes could be improved. For bare soil usually it is difficult to locate enough and proper reference areas to train the classifier.



N = 368	precision	recall	F1 score
Urban	0.86	0.82	0.84
Cropland	0.77	0.94	0.85
Pasture/meadow	0.65	0.81	0.72
Bare soil	1.00	0.40	0.57
Forest	0.88	0.94	0.91
Scrubland/grassland	0.78	0.54	0.64
Water	1.00	0.87	0.93
Wetland	0.86	0.67	0.75
accuracy			0.84

Figure 64: Accuracy estimation of classification in Passauna

In addition, also classification methods using Neural Networks were tested for the projects requirements in MuDak-WRM. Classificators based on Neural Networks have usually advantages in particular circumstances, e.g. if the reference areas are imported from a huge GIS-database and can be used for an automatic learning process. For MuDak-WRM we did not find advantages to use the Neural Networks.

Urban Soil Sealing

The estimation of the Urban Soil Sealing was an important factor for different models and estimations in the other WPs. The estimation was done on the basis of Sentinel-2 data and the land cover classification. Hence the ground pixel size was 10m and the revisit time of the satellite was 5 days. Because of the use of optical images there was a dependency of cloud free scenes, that means in reality there will be less images than every 5 days. The specifications by the project partners for this product was to have 1 Urban Soil Sealing estimation per year.

As the basis for the method generation of this product the definition of the Copernicus HR Layers was used:

> *The imperviousness products capture the percentage and change of soil sealing. Sealed/Impervious areas are characterized by the substitution of the original (semi-) natural land cover or water surface with an artificial, often impervious cover. These artificial surfaces are usually maintained over long periods of time. The imperviousness HRL captures the spatial distribution of artificially sealed areas, including the level of sealing of the soil per area unit. (https://land.copernicus.eu/pan-european/high-resolution-layers/imperviousness)*

Hence the point is to deal with the soil sealing created by humans though constructions. That means that it is necessary

- to map the Urban Areas
- to determine the sealing on a raster of 10 x 10m.

Simplified it is possible to divide the Urban Area completely into three components (see (Ridd 1995)): 1. built-up/sealed areas, 2. bare soil, sand and 3. Vegetation. We assign to these components these typical values for Urban Soil Sealing:

1. built-up/sealed areas: 100%
2. bare soil, sand: 0%
3. Vegetation: 0%

For every pixel in the raster the portion of the three components has to be estimated and the assigned values of the particular Urban Soil Sealings have to be accumulated due to the estimated portions.

In MuDak-WRM the realization of this approach was done by the following steps:

1. Urban areas are selected by using the result of the land cover classification (see above). As an alternative it is also possible to use existing data (e.g. Open Street Map, governmental data etc.).
2. Within the borders of urban area the pixels with the class bare soil/sand are selected. These pixels are assigned to the urban soil sealing value 0.
3. The remaining urban area is pixelwise assigned to a value of urban soil sealing between 0-100%. The value is computed, based on the inverse correlation with the vegetation cover fraction. Here the NDVI (Normalized Difference Vegetation Index) is used as as proxy for vegetation cover fraction.

A result can be seen in Figure 65.

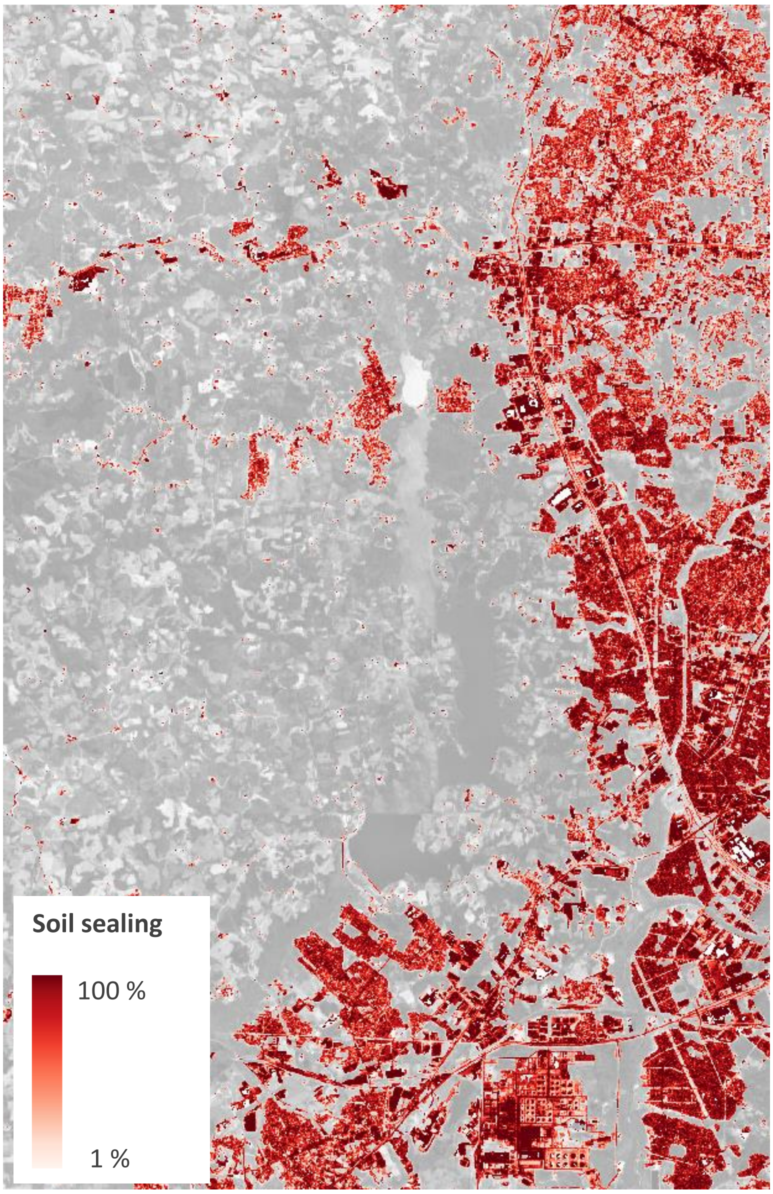


Figure 65: Result of Urban Soil Sealing for Passaúna test area in 2018.

Surface Albedo

Surface Albedo quantifies the fraction of the sunlight (0,29 – 4,0 µm) reflected by the surface of the Earth. It describes the 'reflectivity' of the Earth's surface. It is an essential input parameter for energy balance calculations, including the estimation of evaporation rates. The estimation of the land surface Albedos was necessary to be used within other WPs of project partners. The common way to use Albedos until now was to use for the whole year values from literature based on the land cover classes. The request from other WPs was to use the real Albedos calculated from satellite images at the requested dates.

The used approach has done the estimation based on Sentinel-2 Level 2A images and the bands with a ground pixel size of 20m. The method is based on (Zhang et. Al. 2018).

The estimation started with a narrow-to-broadband conversion from discrete Sentinel bands (0.4 to 2.4 µm) to shortwave bidirectional reflectance (0,29 – 4,0 µm). In a second step a correction of systematic deviations was done by using the spatially and temporally corresponding MODIS Albedo product (MCD43) with a resolution of 500m by an adaption of the Albedo values via image statistics.

As the second step with the use of MODIS means an additional dependency on another satellite sensor and it is not sure how long MODIS will work in the future, the second step was integrated optionally and turned off for the generation of the last products in MuDak-WRM.

As a requirement from the project partner the Albedo was created one time per month. For that all cloud free Sentinel-2 images of a month were used to estimate the Albedos and then to accumulate them to one Albedo for the month.

In Figure 66 the results of the Albedo created for the Brazilian test site Passauna for April 2018 can be seen.

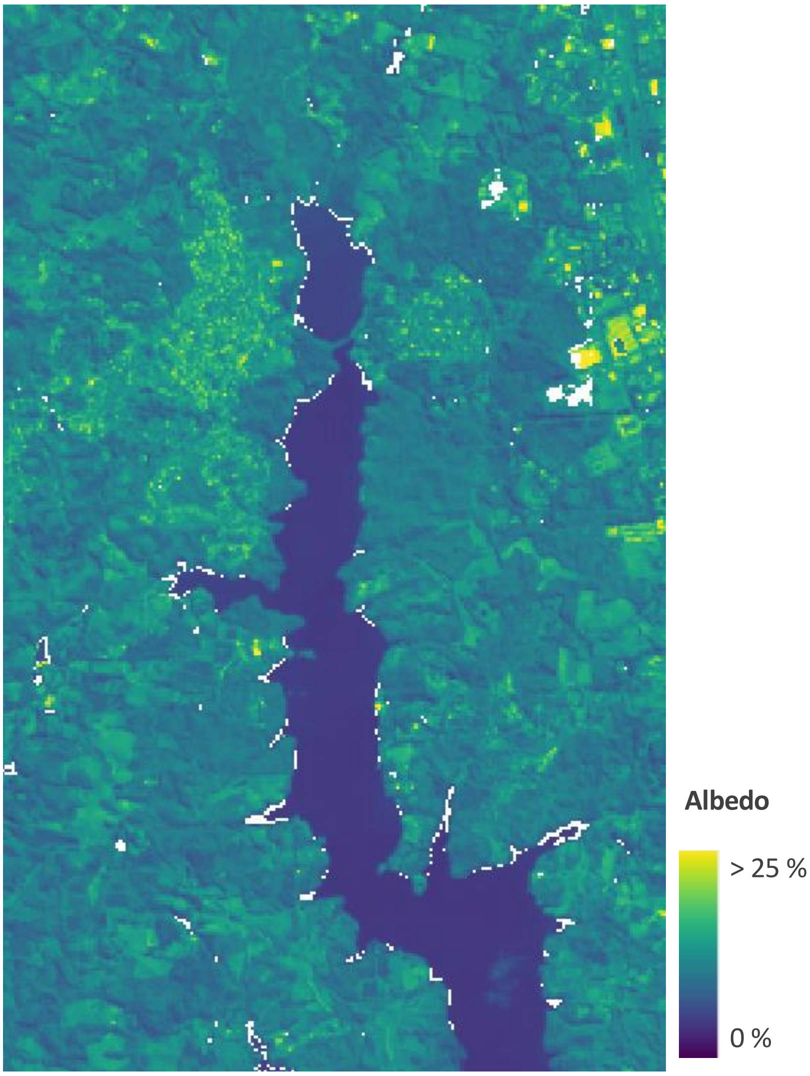


Figure 66: Surface Albedo created for Passauna test area for April 2018

LAI (Leaf Area Index)

The estimation of the LAI was also necessary to be used in models of other WPs. The Leaf Area Index quantifies the one-sided green leaf area per unit ground surface area, thereby characterizing plant canopies. It is an essential parameter for the estimation of evapotranspiration. The method used for the implementation was based on (Weiss, 2016). A validation by out project partners came to the result, that in two areas the results of the LAI approach were improvable: In forest areas and also in areas with very low vegetation. We improved the results in that areas by using NDVI-based values.

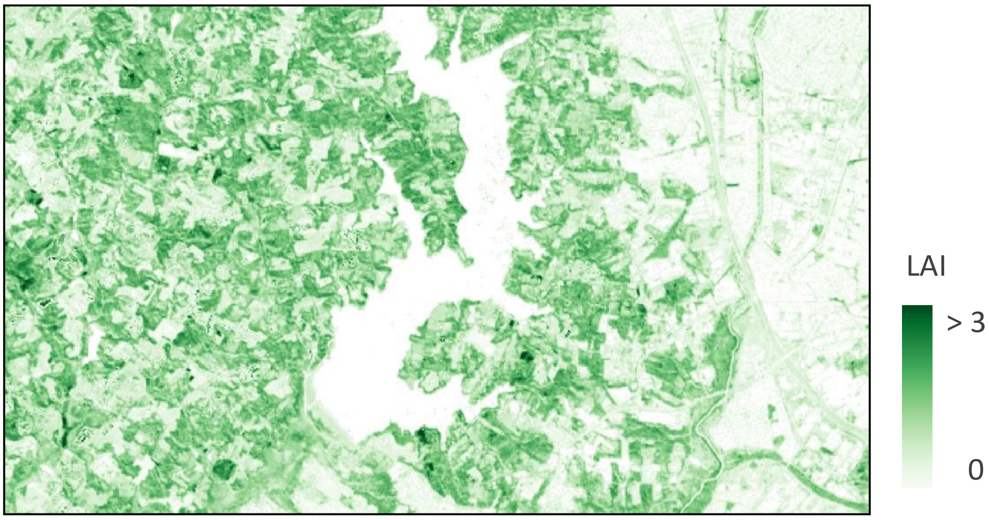


Figure 67: Result of LAI calculation for Passauna area in June 2018

In Figure 67 the LAI-calculation for the Passauna test area in Brazil is depicted for June 2018. Because of the dependency from cloud free images of Sentinel-2 the realization of this method in MuDak-WRM use all images of a month to be able to find cloud free areas and composite them to monthly products. Figure 68 shows the monthly calculation for the Passuana area. For all month, except for October, we were able to produce LAI-images. In October it was not able to find cloud free scenes.

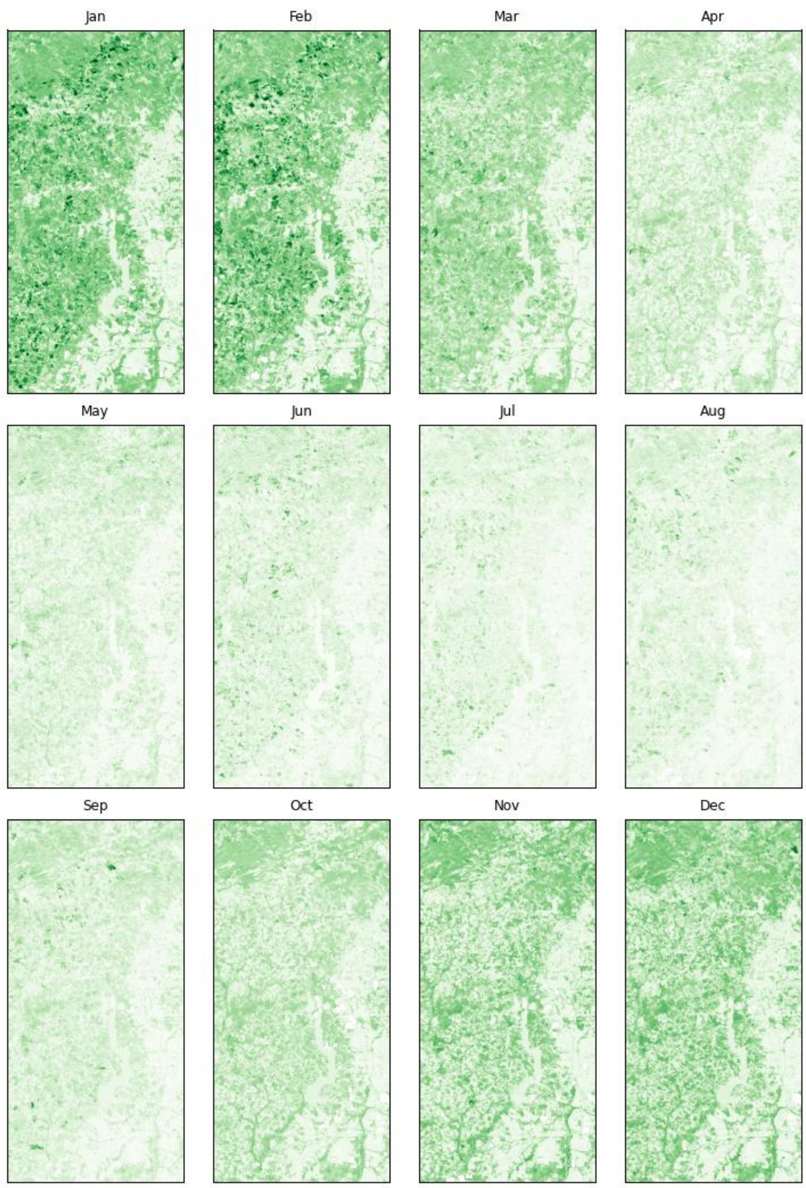


Figure 68: Result of monthly LAI calculation for Passauna area for 2018. Darker tones represent a higher leaf cover.

In Figure 69 the course of the mean LAI-values for different land cover classes through the year 2019 in the German test area Grosse Dhünn is depicted, merged to single months. As expected, the values are usually the highest for the classes forest and pasture, for the other classes the values are low. Also observable in the graph is the increase of the values for the summer, as expected and the decrease to the winter.

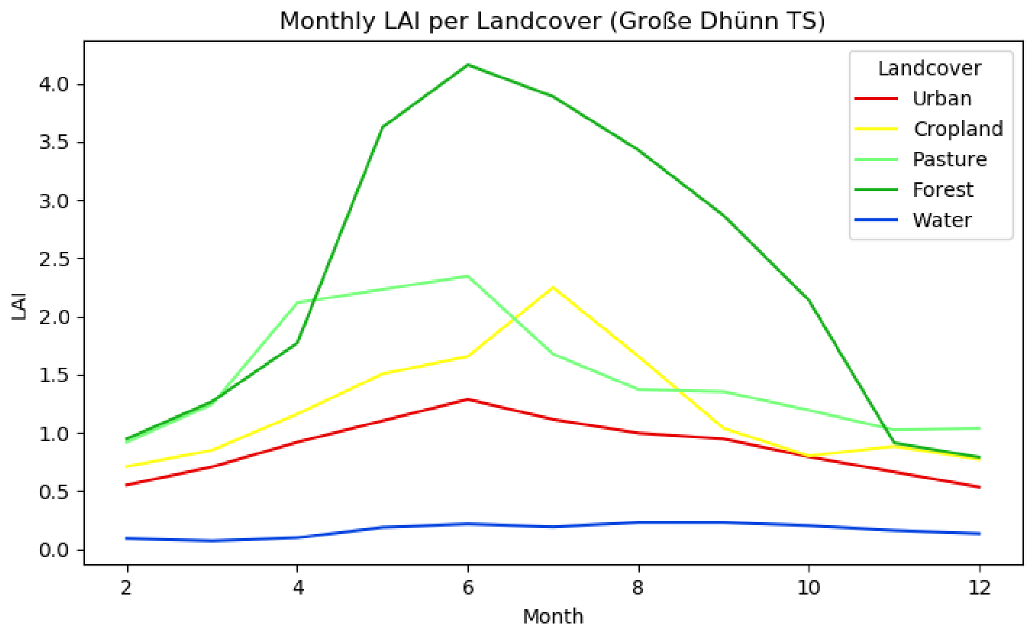


Figure 69: LAI per land cover for German test area Große Dhünn

Chlorophyll-a

The Chlorophyll-a (Chl-a) concentration and Total Suspended Matter (TSM) in water bodies were calculated from pixels of the water surface und used to do a monitoring of the water bodies. For that the „Case 2 Regional Coast Colour“ (C2RCC) Processor – implemented in the SNAP Toolbox – was chosen (based on (Brockmann, et al., 2016). The C2RCC processor utilizes trained neural networks und requests Sentinel-2 Level 1C data as input. C2RCC executes an atmospheric correction implicitly. It calculates Chl-a and TSM based on Sentinel-2 single scenes, hence a calculation of that products is possible every 5 days, if the investigation area is cloud free.

A calculation for Chl-a and TSM is depicted in Figure 70 for the Brazilian test area Passauna for the dates 20.04.2018, 14.07.2018, 19.07.2018, 09.02.2019 and 03.08.2019.

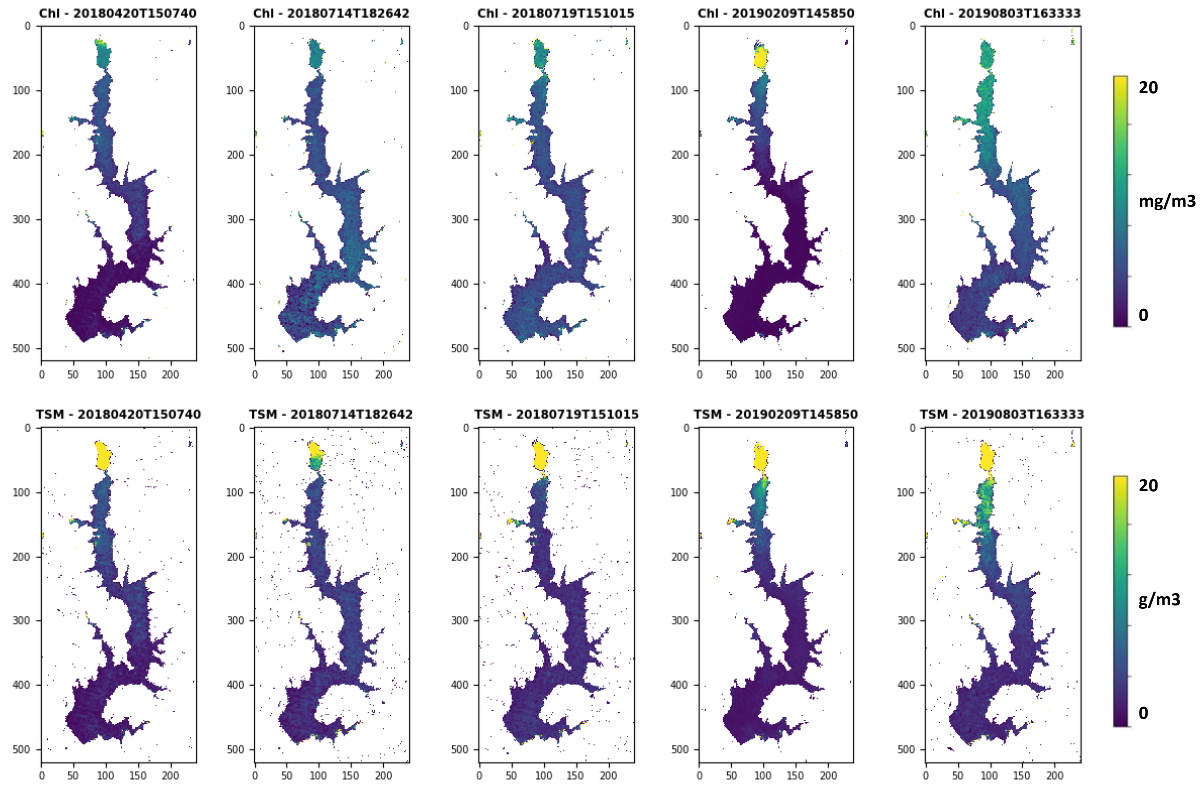


Figure 70: Result for Chl-a (higher row) and TSM (lower row) calculation for Passauna test area

Surface Temperature

The calculation of the surface temperature is a good way to do a monitoring of the different areas with an area-based method in a regular raster. That means compared to point-wise measurements an area-wise supervision of particular areas is possible. The used calculation of the temperature was based on (Yu et al., 2014), (Sobrino et al. 2008) and (Barsi et al. 2003). For the calculation of the surface temperature images from the Thermal Infrared Sensor (TIRS) of Landsat-8 are used. For the conversion from radiance to surface temperature the mono-window algorithm was selected (Qin et. Al., 2001). The final temperature product has a resolution of 30m (but based on bands with 100m resolution) and is every 16 days available, based on the repetition rate of Landsat-8.

In Figure 71 the result of the calculation for the German test area Große Dhünn is depicted for 29.06.2019.

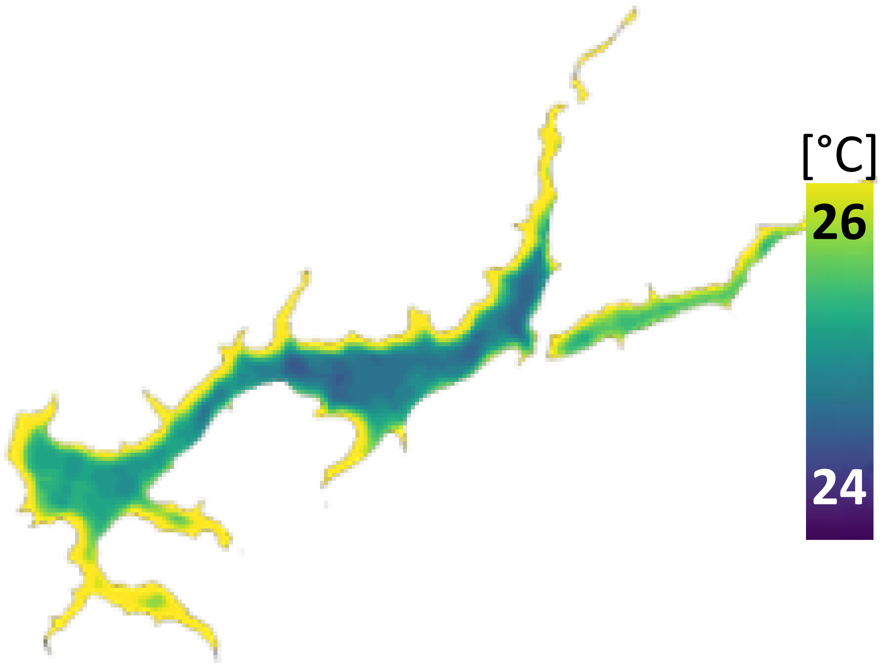


Figure 71: Water Surface Temperature calculated for test area in Germany at Große Dhünntalsperre for 29.06.2019

5.5.3. Summary and conclusions

In WP 5 we successfully analyzed the demands of the water management community through the different project partners in Germany and Brazil and were able to find out which methods and products were needed and we developed them. The used strategy was to develop the methods first for the German test site Große Dhünn and extend the developments to the second test site in Brazil, to Passauna. The aim of this strategy was to develop methods in a way to be able to use them nearly all over the world in regions with different levels of development.

During MuDak-WRM we developed and tested mainly the following products:

- Land Cover Classification
- Urban Soil Sealing
- Surface Albedo
- Leaf Area Index
- Chlorophyll-a Concentration and Total Suspended Matter
- Surface Temperature

In summary this project was for EFTAS a good possibility to extend the knowledge in the area of water management demands and methods and to develop methods which are requested in this area. The cooperation with the German and Brazilian partner was very effective and good. This is a reason why EFTAS can imagine a successful future cooperation with all project partners, with the Germans and the Brazilians.

References of WP 5:

Barsi, J.A., J.L. Barker, and J.R. Schott. 2003. “An Atmospheric Correction Parameter Calculator for a Single Thermal Band Earth-Sensing Instrument.” In IGARSS 2003. 2003 IEEE International Geoscience and Remote Sensing Symposium. Proceedings (IEEE Cat. No.03CH37477), 5:3014–16. Toulouse, France: IEEE. https://doi.org/10.1109/IGARSS.2003.1294665.

Breiman, Leo. 2001. “Random Forests.” Machine Learning 45 (1): 5–32.

Brockmann, C.; Doerffer, R.; Peters, M.; Stelzer, K.; Embacher, S.; Ruescas, A. Evolution of the C2RCC neural network for Sentinel 2 and 3 for the retrieval of ocean colour products in normal and extreme optically complex waters. In Proceedings of the ESA Living Planet, Prague, Czech Republic, 9–13 May 2016

Qin, Z.; Karnieli, A.; Berliner, P. A mono-window algorithm for retrieving land surface temperature from Landsat TM data and its application to the Israel-Egypt border region. Int. J. Remote Sens 2001, 22, 3719–3746.

Ridd, M. K. 1995. “Exploring a V-I-S (Vegetation-Impervious Surface-Soil) Model for Urban Ecosystem Analysis through Remote Sensing: Comparative Anatomy for Cities†.” International Journal of Remote Sensing 16 (12): 2165–85. https://doi.org/10.1080/01431169508954549.

Sobrino, Jose A., Juan C. Jimenez-Munoz, Guillem Soria, Mireia Romaguera, Luis Guanter, Jose Moreno, Antonio Plaza, and Pablo Martinez. 2008. “Land Surface Emissivity Retrieval From Different VNIR and TIR Sensors.” IEEE Transactions on Geoscience and Remote Sensing 46 (2): 316–27. https://doi.org/10.1109/TGRS.2007.904834.

Weiss, Marie. 2016. “S2ToolBox Level 2 Products:LAI, FAPAR, FCOVER Version 1.1.” Sentinel 2 ToolBox Level2 Products. https://step.esa.int/docs/extra/ATBD_S2ToolBox_L2B_V1.1.pdf.

Yu, Xiaolei, Xulin Guo, and Zhaocong Wu. 2014. “Land Surface Temperature Retrieval from Landsat 8 TIRS—Comparison between Radiative Transfer Equation-Based Method, Split Window Algorithm and Single Channel Method.” Remote Sensing 6 (10): 9829–52. https://doi.org/10.3390/rs6109829.

Zhan Li, Angela Erb, Qingsong Sun, Yan Liu, Yanmin Shuai, Zhuosen Wang, Peter Boucher, Crystal Schaaf, 2018. „Preliminary assessment of 20-m surface albedo retrievals from sentinel-2A surface reflectance and MODIS/VIIRS surface anisotropy measures”, Remote Sensing of Environment, Volume 217, Pages 352-365, ISSN 0034-4257, https://doi.org/10.1016/j.rse.2018.08.025.

5.5.4. Flyer

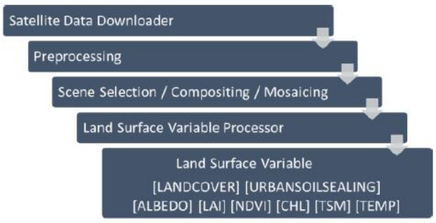
MuDak-WRM

FONA Research for Sustainable Development BMBF

Sponsored by the Federal Ministry of Education and Research

Satellite Remote Sensing for Reservoir Catchment Monitoring

Satellite remote sensing provides means to acquire spatially explicit information on land cover change and vegetation dynamics. A major asset of these mapping products is that they can be globally obtained in a highly automated, cost-effective manner. Thus remote sensing contributes to reservoir monitoring by quantifying terrestrial substance outputs on large scales complementing in-situ observations.



Satellite Data

The Sentinel-2 multispectral satellites of the European Copernicus program acquire high spatial resolution (up to 10 m) data with a temporal revisit time of at least 5 days. These time series are compiled to datacubes representing defined windows in space and time. Processed to selected land surface variables these data quantify the status and change of land cover as well as intra-/interannual vegetation dynamics as factors of terrestrial substance outputs and reservoir water quality.

Processing Chain

An automated processing chain was established aiming at generating data which is globally available transferable and cost efficient.

The processing chain comprises the download of satellite time series data from the data providers as well as preprocessing operations such as atmospheric correction. A further downstream component handels multispectral time series datacubes, supporting the selection of scenes and pixels based on quality criteria (e.g. absence of clouds, cloud shadows, snow) temporal aggregation for cloud-free composites. Finally a land surface processor is applied.

Land Surface Variables

(A) Land cover: Describes the physical or biological coverage of the Earth's surface. It can be linked to (human) land use and associated pollutant emissions. Moreover, it is the basis for erosion modeling.

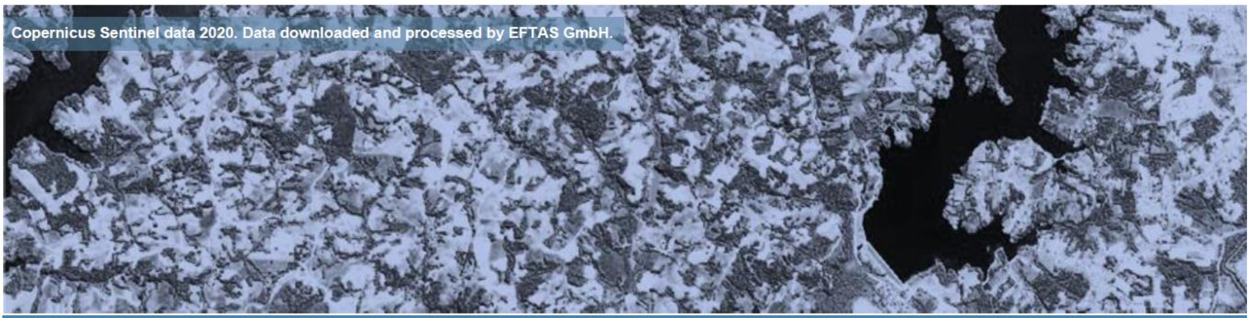
(B) Urban Soil Sealing: Provides detailed information on the permeability of settlement areas, which impact surface runoff and substance transport as well as microclimatic processes.

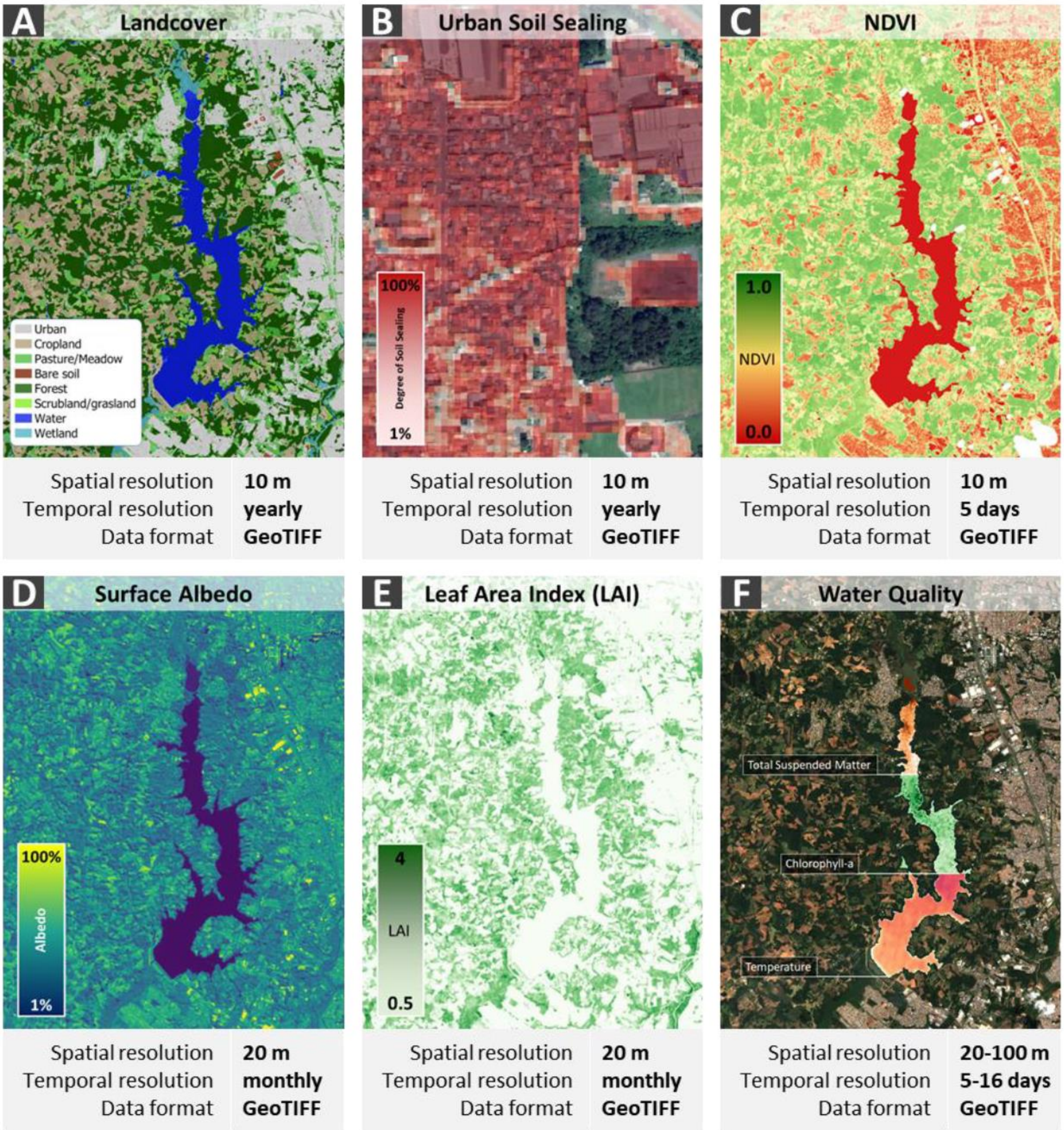
(C) NDVI: The Normalized Difference Vegetation Index (NDVI) provides proxy information on biomass and vitality of vegetation. It supports erosion modeling with vegetation periods information.

(D) Surface Albedo: Describes the 'reflectivity' of the Earth's surface. It is an essential input parameter for energy balance calculations, including the estimation of evaporation rates.

(E) Leaf Area Index: Quantifies the one-sided green leaf area per unit ground surface area, thereby characterizing plant canopies. It is an essential parameter for the estimation of evapotranspiration.

(F) Water Quality: Chlorophyll-a, Total Suspended Matter and Temperature are obtained from water surfaces to monitor and model water quality on a large scale.





Authors Wolf, N.; Pakzad, K.
Contact Kian Pakzad
Funded by Federal Ministry of Education and Research, BMB
Web www.mudak-wrm.kit.edu

5.6. Work package 6 – Water quality assessment

5.6.1. Introduction and objectives

For the management of reservoirs the comprehension of the system dynamics is fundamental to assure water quality. For that the first step is measure key physical, chemical and biological parameters to make qualitative and quantitative assessments, and later identify the main acting forces and how they are connected.

The water quality of reservoirs is commonly evaluated in terms of concentrations of nutrients and algae (chlorophyll), and water transparency (secchi depth). These parameters form the basis for calculating trophic state index. Therefore, the knowledge on the actual trophic state should be combined with the assessment of the fate of nutrients inside the reservoir. Their fate is controlled by hydrodynamics and meteorological conditions. For example inflowing nutrient loads can be stored through sedimentation or promote algae growth near the water surface. Decision making in water quality management requires a mechanistic understanding of the governing hydrodynamic processes their ecological impacts.

The strong spatial and temporal variability of physical forcing conditions in reservoirs necessitate data collection of water quality parameters with high-frequency, accuracy and precision. Employing sensors equipped with advanced technology, such as optical measurements and on-line monitoring, can represent a significant advance for water monitoring strategies. Together with classical laboratories analysis, this approach can be key to define minimum monitoring strategies, and promoted an improvement in water quality control techniques to streamline decision-making processes and generate savings in water treatment.

5.6.2. Preparation and method

WP6 addressed two main objectives:

(1) Collection of ground-truth data to support other WPs in diverse purposes. Such as WP1 and WP2 that were developing methodologies to assess the storage of the reservoir (by means of water balance and sedimentation rates), the implementation of hydrodynamic and water quality models of WP3, validation of remote and close sensing data provided by WP4 and WP5 and the integration of the data to an online interface provided by WP7.

(2) Investigating the processes associated with the observed water quality in order to understand the fate of dissolved and particulate nutrients and organic matter inside the reservoir and evaluation of combinations of classic laboratorial sample analysis with continuous monitoring made by sensors for minimum monitoring strategies. For this part, we analyzed relationships between monitored water quality parameters and hydrodynamic, meteorological and operational boundary conditions.

5.6.3. Approach

In order to achieve our goals Passaúna reservoir was monitored for a period of one year, from February 2018 to February 2019. The high resolution monitoring took place mainly at the Intake region (Figure 72), where a platform was installed. We measured vertical profiles of flow velocity and temperature, dissolved oxygen concentration at the bottom and at the water surface, as well as several key water quality parameters through the optical sensors provided by TriOS (see Table 8 for details) and one additional fluorometer, which were deployed close to the water surface.

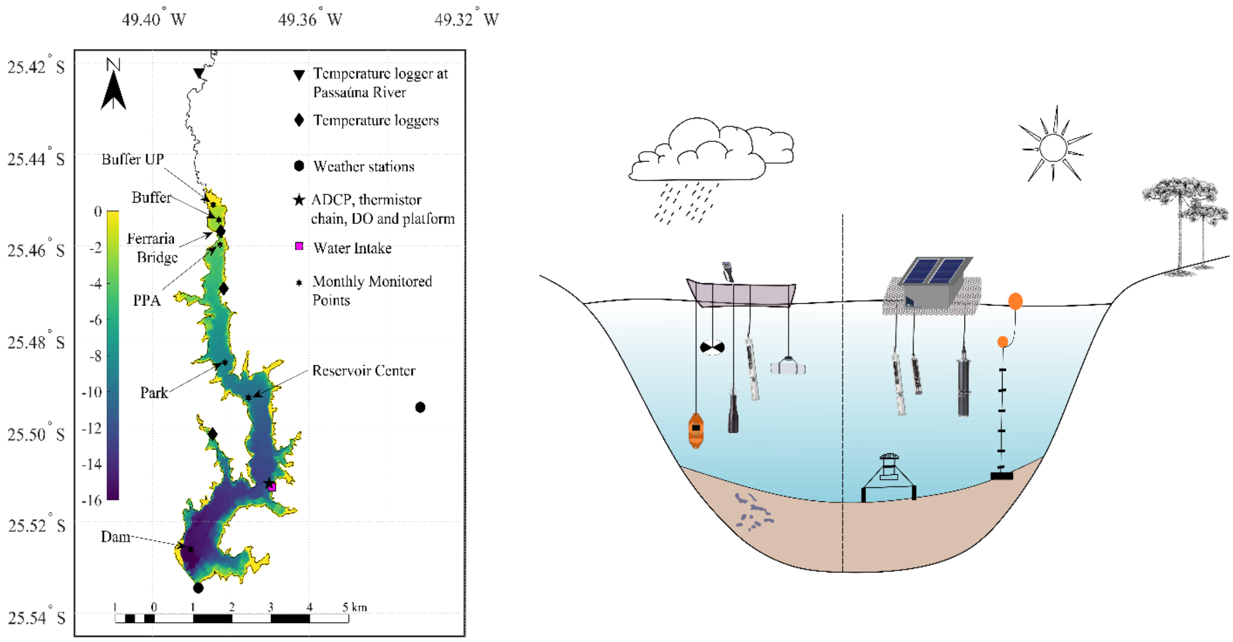


Figure 72: Left panel: Bathymetric map of Passaúna reservoir (provided by WP1) with the indications of monitored points during campaigns and location of the continuous monitoring platform, temperature loggers and meteorological stations. Right side: sketch of the monitoring scheme of the campaigns (left side of the dotted line) and the continuous monitoring platform (right side of the dotted line).

During three intensive measurement campaigns (February 2018, August 2018 and February 2019), several points along the reservoir were chosen to collect water samples to laboratorial analysis of nitrogen, phosphorus and suspended solids, dissolved organic carbon and chlorophyll-a (Figure 72). Sampling was also performed along the water column at each location, thus providing the distribution of all parameters along the longitudinal direction and depth. In parallel with the sampling, measurements with sensors were conducted, first with the profiling of the monitoring points and later with the spatial continuous longitudinal transects. Except for the continuous sensor measurements along longitudinal transects, the sampling conducted during the intensive campaigns was conducted at a monthly basis, for a reduced number of sampling sites.

Table 8: Overview of the target processes and the corresponding measurement methods used in the reservoir. The measurement mode is either continuous measurement (minute resolution) at a representative sample point (CM), quasi-continuous measurement in monthly or event-related individual measurements (QM), spatially distributed high-resolution Measurements during the measurement campaigns (C).

Target process	Measurement method	Mode
Temperature, mixing and stratification dynamics	Vertical profiles of temperature (11 water depths)	CM
Inflows and side arm temperature influence on stratification	Temperature at key locations along the reservoir	CM
Density currents and vertical distribution of particles in the water column	Vertical profiles of acoustic backscatter strength, particle size distribution along the longitudinal, temperature profile and temperature of tributaries	C QM CM

Turbulent vertical mixing in the reservoir (dissipation rate of turbulent kinetic energy and turbulent diffusivities)	High-resolution vertical profiles of flow velocities using an acoustic current profiler (ADCP) deployed at the bottom of the reservoir. Temperature profiles	CM
Water quality assessment through chlorophyll concentration and species composition (algae groups). Water quality dynamics – link with hydro-meteorological processes	Anchored sensors near the surface, point profiling and longitudinal transects: Total chlorophyll, green algae, cyanobacteria and diatoms	CM QM C
Minimum monitoring strategies with the combination of traditional sampling with sensors. Water quality dynamics – link with hydro-meteorological processes	Anchored optical sensors near the surface: Absorption spectra in the range of 200 – 360 nm to derive Nitrate, CODeq, BODeq, DOCeq, TOCeq and SAC254 plus cyanobacteria, chlorophyll-a and CDOM measured by fluorescence.	CM
Fate of nutrients and organic matter inside the reservoir Water quality dynamics – link with hydro-meteorological processes	*Vertical profiles* <u>Sensors:</u> Conductivity, temperature, dissolved oxygen, turbidity, pH, salinity, Nitrate, CODeq, BODeq, DOCeq, TOCeq, chlorophyll-a, green algae, cyanobacteria, diatoms, cryptophyta, sediment size distribution <u>Laboratorial analysis:</u> DOC, chlorophyll-a, fluorescence, phyto and zooplankton identification, nitrogen series, phosphorus series and solids series *Continuous longitudinal transect* Temperature, chlorophyll-a, green algae, cyanobacteria, diatoms, cryptophyta, particle size distribution	QM C

List of sensors – e.g. **Sensor name (brand/producer):** parameters measured

OPUS (TriOS): Absorbtion spectrum (200-360 nm), N-NO3, CODeq, BODeq, DOCeq, TOCeq, SAC254

nanoFlu (TriOS): Chlorophyll-a, cyanobacteria, CDOM

FluoroProbe (bbe): Total chlorophyll, green algae, cyanobacteria, diatoms, cryptophyta

CTD (SonTek): Conductivity, temperature

U-53 (Horiba): Dissolved oxygen, pH, turbidity, salinity and conductivity

AP-800 (AQUAREAD): Dissolved oxygen, pH, turbidity, salinity and conductivity

LISST (Sequoia): In-situ particle size distribution

ADCP (Nortek): Horizontal flow velocities, high-resolution vertical flow velocities, acoustic backscatter strength

5.6.4. Results and outcomes

The first main goal of WP6 was achieved by providing a ground-truth data that were used by other WPs during the project. An overview of the continuous measurements are shown in Figure 73, while single campaigns are listed on Flyer 1.

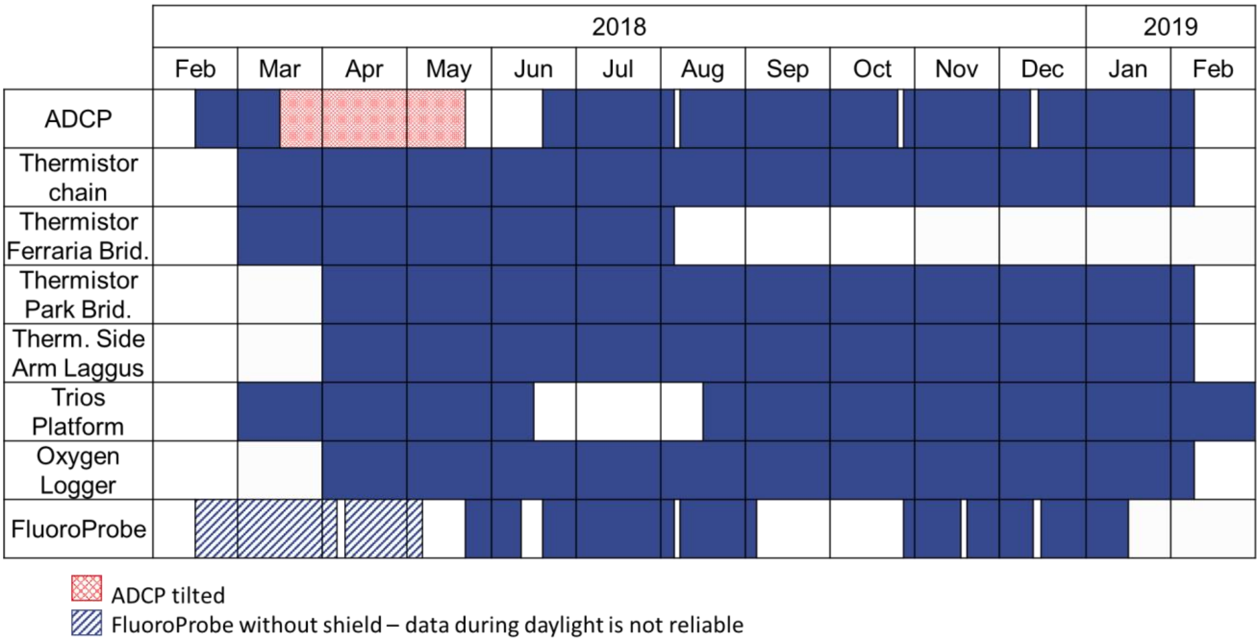


Figure 73: Overview of the acquired data over the monitoring period.

The combination of several parameters provided understanding of the stratification patterns of Passaúna reservoir. It is characterized by a seasonal mixing period with intermittent periods of weak stratification, and a persistently strongly stratified period during spring and summer. Mixing was mainly driven by convection during periods of decreasing air temperature and stratification was formed not only by warming at the water surface by the solar radiation, but also by the influence of lateral flows (Flyer 2). The polymictic mixing pattern suggests a high importance of internal load of nutrients, because even under weak stratification during the mixing season, dissolved oxygen concentration on the deeper water layers decreased considerably, which is a trigger for the dissolution of nutrients from the sediment. Results indicated high loads of the inflow and decreasing concentrations along the longitudinal axis of the reservoir (Flyer 1). Phosphorus can be released from the sediment during stratified periods and subsequent mixing could result in the degradation of water quality. Such situations, however, were not observed at problematic levels. In addition, the fate of nutrients brought by the Passaúna River depends on the interplay of inflow conditions and stratification of the reservoir, since the inflow forms a density current. We observed that the forebay region (located before the constraint created by Ferraria Bridge) had an important role on the formation of the density currents. By increasing the inflow temperature, the forebay promotes density currents that bring the inflow to upper layers of the water column in the reservoir. Therefore, future changes of the inflow temperature, e.g., in the absence of the forebay due to siltation or changes in stream shading in the catchment, will affect not only the thermal regime of the reservoir, but also its water quality.

For the monitoring set up combining sensors and classical laboratories analysis, we observed that both are required to design action plans (Flyer 3). The sensors need the laboratorial results for calibration and interpretation of the acquired data. On the other hand the sampling cannot be conducted at high frequency, thus the sensors can observe the parameters continuously and fill the gaps left between the campaigns. Continuous observations can be related to hydrometeorological conditions to provide a better comprehension of the dynamics of the system. With this set up, we intend to have insights to assist in advances in protocols for minimum monitoring strategies.

In addition, new approaches for measurements were developed as part of the project: Flyer 4 describes an evaluation of suspended solids in inflowing water and within the reservoir by combining acoustic measurements and laboratory analyses of discrete water samples. These methods have been used for characterizing density currents in the reservoir. In Flyer 5 we describe how qualitative and quantitative analyses of dissolved organic matter (DOM) facilitates a better understanding of water quality dynamics in reservoirs.

Other examples of WP6 outcomes are listed at the following section. Continuing effort will be spend on presenting the obtained results in scientific publications . An overview on the status of these publications is provided at the end of this section.

5.6.4.1. Problems and lessons learned

ADCP: Over the monitoring period the deployment of the ADCP was improved to increase quality of the data. Adjustments in the configuration were made after the first deployment and analysis of the results. Deployment periods were initially planned for 3 months, however the instrument flipped over after 20 days and subsequent data could not be used. For this reason the deployment period was shortened to reduce the risk of similar problems.

FluoroProbe: The device that measured the different algae groups was anchored at the first two periods with a wiper that cleaned the optical sensor. The wiper precluded the use of a shield around the sensor beam to protect it from sunlight, which can interfere with measurements. After the second deployment it was clear that there was no need to use a wiper since there was no growth of biofilm in the sensor, from that point on the shield was mounted and the quality of the data was improved.

Temperature: Unfortunately the logger of temperature placed under Ferraria Bridge got lost. It provided insights about the density currents and there are records only for the first half of the year. We do not know for sure the circumstances under which the sensor disappeared, but since the water level was getting lower it can be the case that it was out of the water and stolen. We should think about better security solutions for sensors that are potential in risk.

Sensor profiling: For the second intensive campaign the project partners reviewed the strategies for sampling and profiling with sensors, hence from there on the campaigns were improved by means of monitoring points, some of them only with sensors, to improve the resolution of the results.

TriOS: The platform unit was composed of a data logger controller, a spectrophotometer sensor (OPUS) and a three fluorometer sensors (nanoFlu). To assure sufficient power supply for measurements (in high temporal resolution) operation over the monitoring period, both data logger and sensors were powered with a self-sufficient photovoltaic system. The procedure of using solar energy only was a TriOS's prototype, tested in this research project.

Another necessary adaptation was related to the system for cleaning probes windows. Usually, this system works with a compressed-air unit, but in Passaúna reservoir this system would consume more energy than the solar system could provide. Therefore, wipers were attached to the probes to promote the window's probes cleaning and to prevent measurement interference. As the measurement technology is optical for such probes, this is a crucial point in order to assure reliable measurements. Two different wipers were used. A brush-type wiper for all nanoFlu together and a double-sided rubber blade wiper for the optical path of OPUS, developed by TriOS in the project. The first worked without any major issues throughout the whole period, while the latter always stopped working after about 2 months and had to be serviced. Improvement of this wiper is on-going work of TriOS.

Additionally, the collected data were transmitted to a cloud in real-time via telemetry, using a modem and a SIM Card (Subscriber Identity Module). The raw data measured by the probes were accessed either in the cloud through an exclusive online platform or downloaded with a flash-driver directly from the data logger.

Lab experiences: Several adaptations in the collection and quantification of suspended solids, nutrients and chlorophyll concentrations were necessary due to, in general, low values found in the reservoir. Higher sample volumes needed to be collected to enable analysis of solids and chlorophyll. During the stratified periods, when iron resuspension occurred, it was necessary to adapt the methodology for measuring nutrients for processes with more acid digestion.

5.6.4.2. Research into use

- Trios sensor adaptations (from WWTP to drinking water reservoir) worked. Sanepar is testing those in different environments and comparing them with conventional sensors. Advantages: Full package of autonomous and telemetric system of high temporal resolution water quality data. Disadvantages: Large structure, due to high energy demand. Need for sensor adaption to each environment.

- Valuable information from relatively cheap temperature sensors, which are easy to install and durable. Disadvantage: product built outside Europe/Brazil. Sanepar and UFPR try to acquire similar sensors for other reservoirs.

5.6.5. Flyers

MuDak-WRM

FONA Research for Sustainable Development BMBF

Sponsored by the Federal Ministry of Education and Research

Water Quality Sensors

Sesnsors were used for real-time continuous monitoring and in-situ evaluation (profiles).

Context

Continuos and in-situ monitoring enables to extend the temporal and spatial frequency of water quality monitoring. Despite the advantages of using optical sensors, their applicability depends on operation, maintenance and calibration to ensure representativeness and to properly indicate the water quality characteristics of the reservoir.

Objectives/Goals

- Evaluate the use of different sensors for water quality monitoring.
- Compare data from sensors and laboratory analysis for calibration and validation of the resuts.

Methods and Equipments

Different sensors were used for the water quality monitoring, considering real-time continuous monitoring (installed at a plataform at inlet) and for in-situ evaluation (profiles during field campaings) [see sensors and application bellow]. The frequency of the profiles perfomed is indicated at the table bellow.

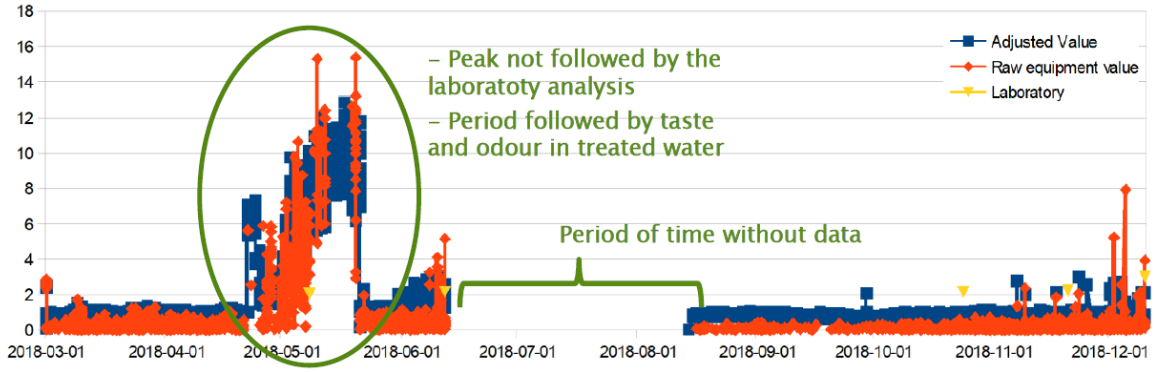
Results

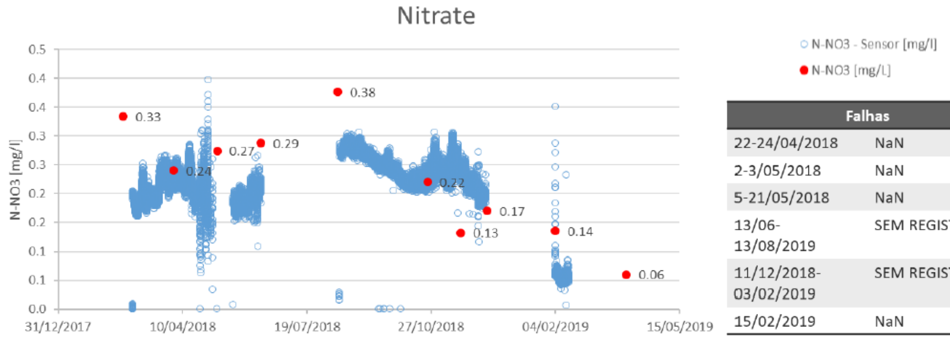
- Nitrate and chloroplyll-a showed good correlation between sensors results and grab samples collected at inlet.
- A peak not followed by the laboratory analysis was observed for dissolved organic carbon. After this period some problems were observed in taste an odour at water supply treatment plant.

U-53	AP-800	CTD	LISST-100 X / 200X	nanoFlu	OPUS	Fluroprobe
HORIBA	AQUAREAD	SonTek	SEQUOIA	TriOS	TriOS	bbe moldaenke
Profiles	Profiles	Profiles	Profiles	Continuous monitoring	Profiles and continuous monitoring	Profiles and continuous monitoring
DO, pH,and conductivity	DO, pH,and conductivity	Conductivity Temperature Depth	Sediment size distribution	CDOM and Chlorophyll-a	Nitrate, CODeq, BODeq, DOCeq, and TOCeq	total chlorophyll, green algae, cyanobacteria, diatoms/brown algae, cryptophytes, fingerprints

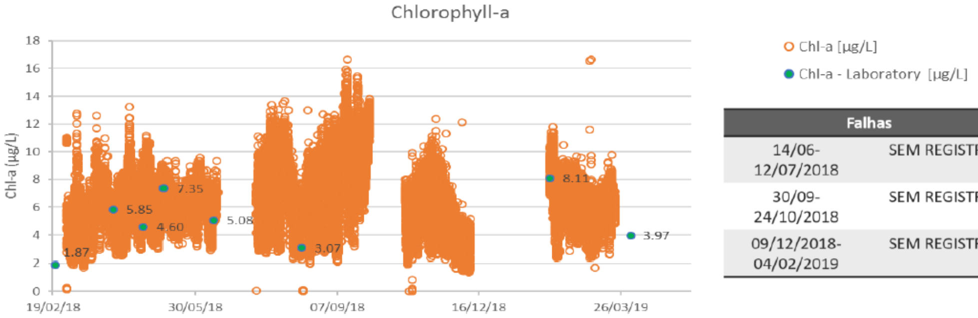
Profiles	2018									2019	
	21-fev	3-abr	24-abr	8-mai	12-jun	13-aug	25-oct	20-nov	11-dec	5-fev	2-abr
U53-Horiba			o	o	o	o					
AP800-Aquaread							o	o	o	o	
CTD-Sontek	o	o	o	o	o	o		o	o	o	o
Fluoroprobe	o				o		o	o	o	o	
Opus-Trios		o	o	o	o	o		o	o	o	o

Figures: Variation of DOC (dissolved organic carbon – adjusted, raw equipament value and laboratory); Nitrate concentration (sensor and laboratory analysis); Chlorophyll -a (sensor and laboratory)





Falhas	
22-24/04/2018	NaN
2-3/05/2018	NaN
5-21/05/2018	NaN
13/06-13/08/2019	SEM REGISTRO
11/12/2018-03/02/2019	SEM REGISTRO
15/02/2019	NaN



Falhas	
14/06-12/07/2018	SEM REGISTRO
30/09-24/10/2018	SEM REGISTRO
09/12/2018-04/02/2019	SEM REGISTRO

Innovation/Outlook

- ✓ Rapid and real-time detection of water quality parameters.
- ✓ Good strategy for reservoir operation, planning and management.

Authors	Gurski, L.; Bernardini, G.; Ungaratti N.; Knapik, H.	Contact	luzi.kotsuka@gmail.com
Funded by	Federal Ministry of Education and Research, BMBF	Web	www.mudak-wrm.kit.edu

MuDak-WRM

FONA Research for Sustainable Development BMBF

Sponsored by the Federal Ministry of Education and Research

Monitoring Passauna's reservoir water quality

Water quality monitoring with field measurements, laboratory analysis, and initial investigations.

Context

Monitoring physical and chemical parameters are important to characterize the reservoir in terms of water quality and hydrodynamic behavior.

Objectives/Goals

- Evaluate Passaúna's reservoir water quality dynamics
- Identify the spatial and temporal variability of Passaúna's reservoir WQ through monthly measurements
- Perfom different analysis to assess the overall interactions between physical, chemical and biological parameters.

Methods and Equipments

Chemical analyses included Nitrogen (Nitrate, Nitrite, Total Ammoniacal Nitrogen, Total Nitrogen), Phosphorus (Orthophosphate, Particulate Phosphorus, Total and Dissolved Phosphorus), Solids (Total Suspended and Dissolved Solids), Chlorophyll-a and Dissolved Organic Carbon (DOC). A summary of field caimpaings are shown in the following Table.

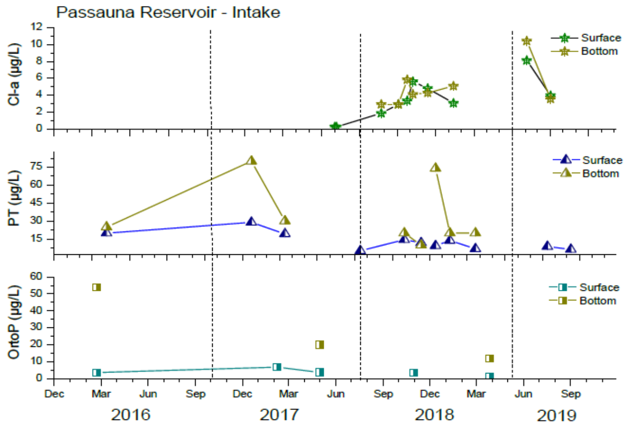
Table 1: Summary of fiel campaings [2018-2019]

Campaigns	Inflow	Buffer	Ferraria Bridge	PPA	Park	Reservoir center	Intake	Dam	Outflow
2018, February	o	o	o	o	o	o	o	o	o
2018, April (03)	o						o		o
2018, April (24)							o		
2018, May	o						o		o
2018, June	o						o		o
2018, July									
2018, August	o	o	o	o	o	o	o	o	o
2018, October	o	o	o	o			o		o
2018, November	o	o	o	o			o		o
2018, December	o	o	o	o			o		o
2019, January									
2019, February	o	o	o	o	o	o	o	o	o
2019, March									
2019, April	o		o	o			o		o

Preliminary Results

- Probable phosphorus retention/assimilation (lower concentrations at outflow while higher concentrations of nitrogen are observed)
- Higher concentrations of TP and TN at inflow and probable retention at buffer region
- Ocurrence of DO decay at bottom layers and concequently changes in gas flux and in phosphorous availability in bottom layers

Figure 1: Variation of chlorophyll-a, total phosphorous and orthophosphate at intake [2016-2019]



Innovation/Outlook/Insights

- Low concentrations in overall parameters analyzed (different approaches for laboratory analysis)
- Differences at inflow→reservoir → outflow: probable assimilation/retention/decay
- Data base for sensors calibration/validation and water quality modeling

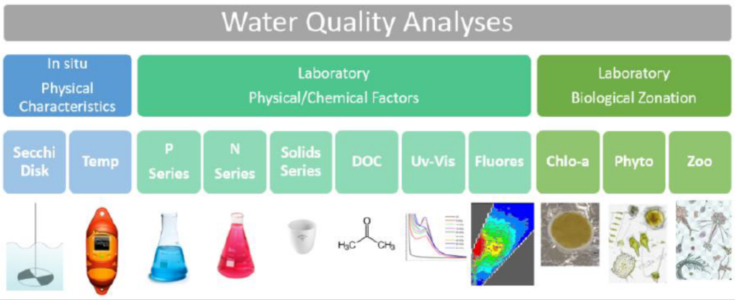


Figure 2: Variation of chlorophyll-a, total phosphorous and total nitrogen in different monitoring sites [2018-2019]

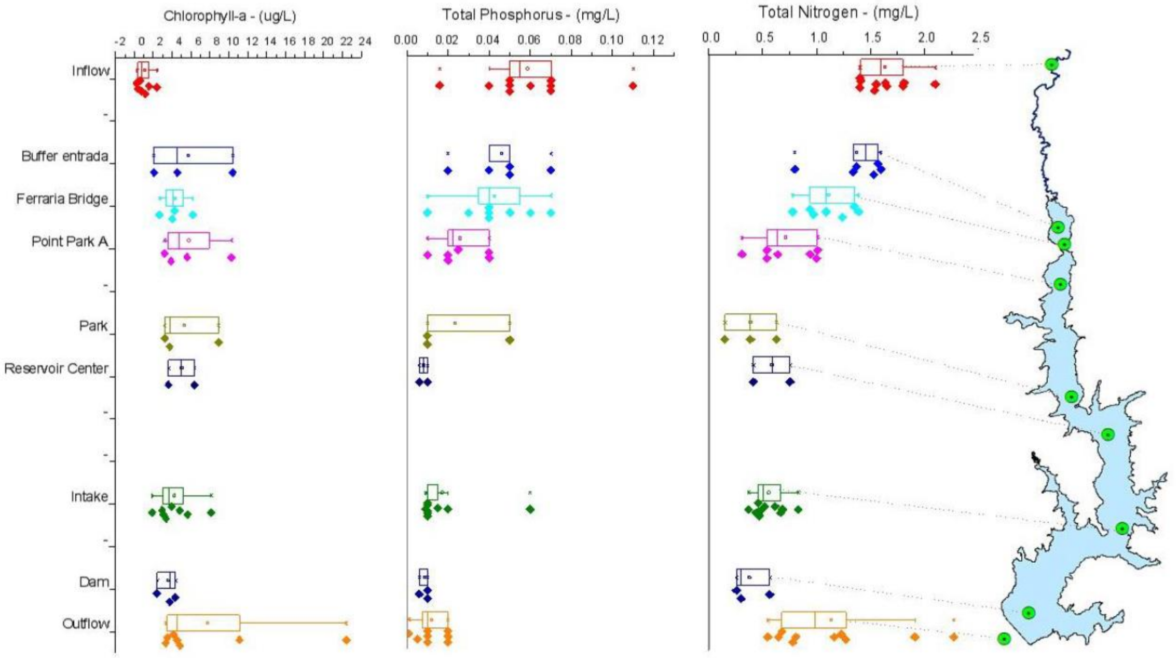
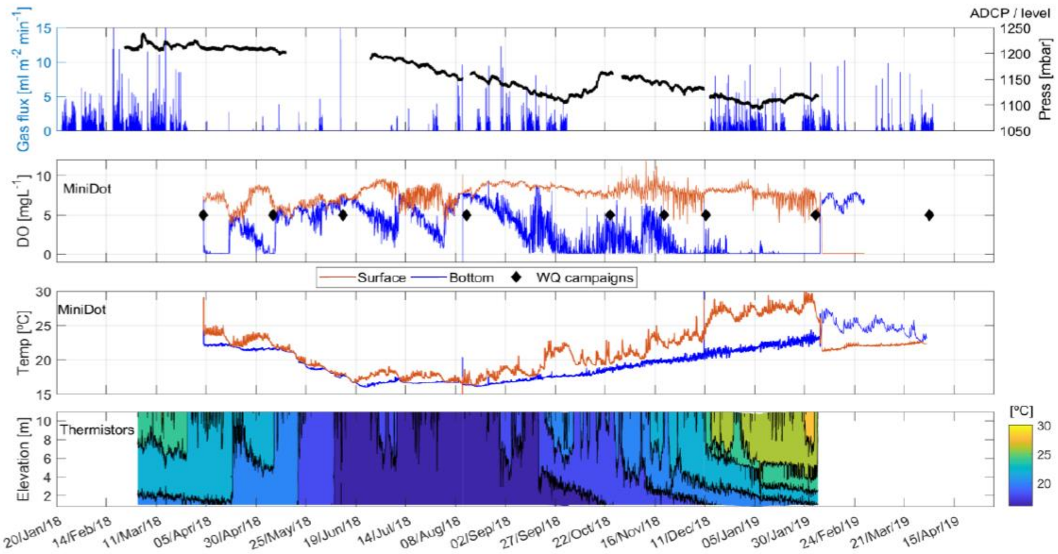


Figure 3: Variation of dissolved oxygen, temperature and gas flux at inlet monitoring site [2018-2019]



Authors Gurski, L.; Marcon, L.; Knappik, H.; Prado, L.
Contact luzi.kotsuka@gmail.com / heloise.dhs@ufpr.br
Funded by Federal Ministry of Education and Research, BMBF
Web www.mudak-wrm.kit.edu

MuDak-WRM

FONA Research for Sustainable Development BMBF — Sponsored by the Federal Ministry of Education and Research

Mixing mechanisms and hydrodynamics of Passaúna Rerservoir

One year of continuous measurements of temperature and dissolved oxygen helped us to identify the key physical mechanisms that govern the mixing processes and also the influence of the Buffer on the reservoir.

Context

River inflows, rich in nutrients and organic matter, can enter the reservoir as underflows along the bottom of the reservoir, favoring the deposition of particles on the sediment. If the inflowing water is lighter (warmer) than the water in the reservoir, it enters as an overflow, delivering nutrients to the photic zone and thus promote phytoplankton growth. Further, the lack of deep-water renewal by underflows and weak vertical mixing promote the formation of hypoxic or anoxic conditions in deeper layers of the stratified reservoir. Oxygen depletion triggers the formation of toxic substances, such as hydrogen sulfide, causes enhanced release of phosphorus and promotes the production and potential emission of the greenhouse gases methane and nitrous oxide. Therefore the comprehension of reservoir hydrodynamics is essential for successful mitigation of adverse effects of reservoir construction, for achieving good water quality and drinking water safety, as well as for predicting future changes.

Objectives/Goals

- Understand the main hydrodynamic processes and drivers of density stratification
- Comprehension on the importance of the Buffer on reservoir hydrodynamics

Method nad Equipment

The measurements were made between February 2018 and February 2019. We measured water temperature in the Passaúna River, after the buffer region and at 11 depths (1 m vertical spacing) in front of the intake station. Two optical oxygen sensors were deployed with the thermistor chain to measure dissolved oxygen concentration near the water surface (at 1 m water depth) and near the bottom (at 2 m above the bed), respectively (Fig. 1).

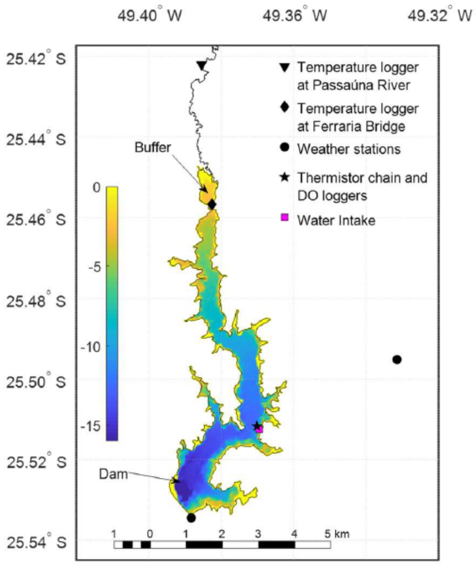


Figure 1 : Map of the study site picturing Passaúna Reservoir, Passaúna River, Buffer and Dam. Locations of monitoring points are indicating in the legend and the colormap shows the depths in meters.

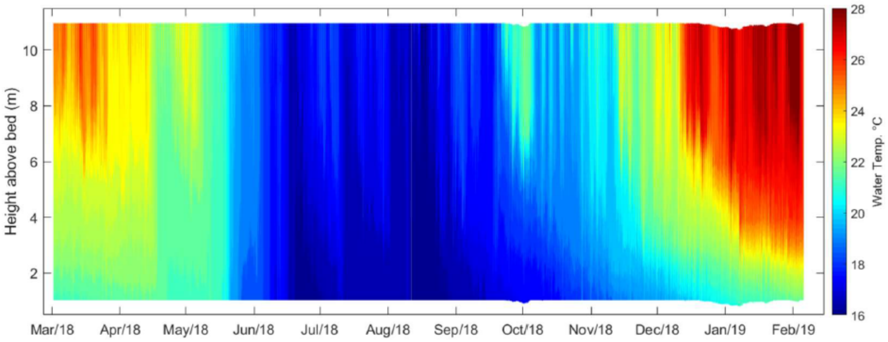


Figure 2: Time series of the measured temperature with the thermistor chain at the Intake region

Results

- Passaúna reservoir was continuously stratified during spring and summer, while frequent mixing and episodic stratification periods were observed during autumn and winter Fig. 2).
- 95 days were mixed from a total of 343 monitored days, representing 72%.
- Observed mixing regime can be classified as discontinuous warm polymictic, it is characterized by more than one mixing period throughout the year and stratified periods lasting for days to weeks.
- Density stratification was particularly strong, related to the strong temperature dependence of density at high temperature.
- Even during shorter periods of stratification during the mixing season, dissolved oxygen concentration near the bottom decreased rapidly (Fig. 3).
- In addition to meteorological forcing, stratification was affected by lateral flows related to river inflow, mainly due to the addition of colder water at the bottom with underflows (Fig. 4).
- The Buffer influences the inflow temperature, and consequently the flow paths into the reservoir.
- For the hypothetical case that the Passaúna River would flow directly into the main reservoir, without passing through the Buffer, the flow path changes towards more frequent underflow situations and lack of overflow (Fig. 4).

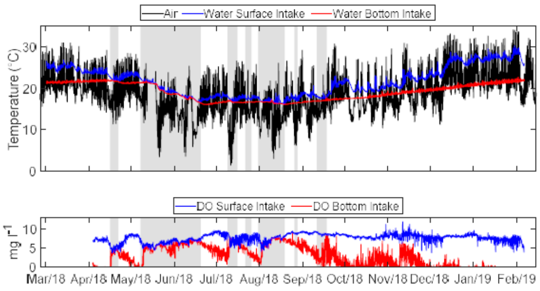


Figure 3 : upper pannel time series of air and water temperatures at the Intake. Lower pannel time series of dissolved oxygen concentrations at the Intake. Grey patches indicate the mixed periods and white areas are stratified.

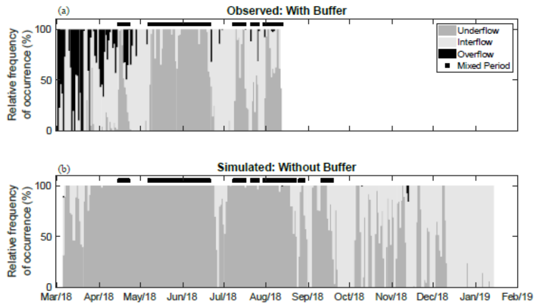


Figure 4: Stacked bar graphs showing the relative frequency of occurrence of different inflow characteristics (flow paths) of the Passaúna River into the main reservoir. (a) Based on observed temperature at Ferraria Bridge. (b) Simulations based on river water temperature measured upstream of the buffer. Data are presented as daily averages of the relative contribution of different flow paths. Square symbols above both panels mark time periods classified as mixed, while during the remaining periods the reservoir was stratified.

Innovation/Outlook

- ✓ High resolution data improved the understanding of reservoir hydrodynamics.
- ✓ Comprehension of the importance of the Buffer for reservoir stratification.
- ✓ Changing inflow conditions without the Buffer, lead to increasing stratification and reduction of the frequency and duration of mixing events. However, bottom water renewal may also reduce the anoxic period's duration.
- ✓ The simulation of inflow dynamics without Buffer can guide the long-term planning for the reservoir operator, as the Buffer is subject to ongoing siltation.

Authors Ishikawa, M.; Bleninger, T.; Lorke, A. Contact ishikawa@uni-landau.de / lorke@uni-landau.de

Funded by Federal Ministry of Education and Research, BMBF Web www.mudak-wrm.kit.edu

MuDak-WRM

FONA Research for Sustainable Development BMBF — Sponsored by the Federal Ministry of Education and Research

SOLIDS: from inflow to outflow and insights

Evaluation of solids contributions at inflow, spatial and temporal variability and insights for laboratory analysis.

Context

Solid analysis allow a better understanding about inputs and transportation throught the reservoir.

Objectives/Goals

- Identify solids fractions and variability from river, reservoir and outflow
- Evaluate the relathionship between solids and turbidity and between solids and accoustic backscatter (ADP-M9 from Sontek®)
- Identify laboratory issues regarding to solids analysis

Methods

Total solids	- Sample is evaporated in a weighted dish and dried to constant weight - Fixed solids: drying oven at 100°C - Volatile solids: ignited at 550°C
Suspended solids	- Solid residue retained by filtering the sample aliquot through a specific pore size filter (0,6 µm) - Volumes from 100 mL up to 1L - Fixed solids: drying oven at 100°C - Volatile solids: ignited at 550°C
Dissolved solids	- Calculated by the difference between total solids and suspended solids

Results

- Good **relationship** between solids, flow and turbidity.
- Higher concentration of **dissolved solids.**
- Evidence of **deposition** throught the reservoir.
- **Low concentrations** demands special filter preparation and higher samples volumes.

Figure 1: Correlation between TS and TSS x Turbidity for three field campaings [Ago/1/, Feb/19, Apr/19]

✓ ST x Turbidity: r=0.6844 and SST x Turbidity: r=0.9653. Better correlation for SST. Dissolved compounds may have important contribution for Passauna's Reservoir.

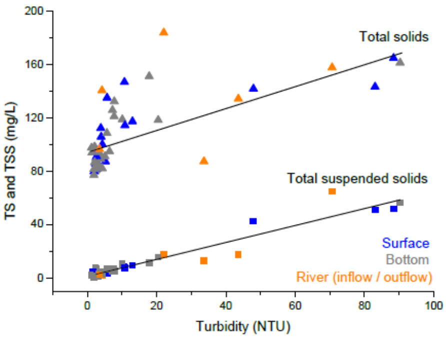
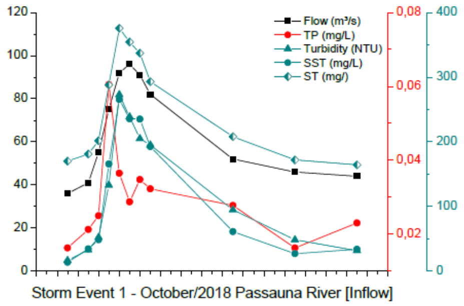
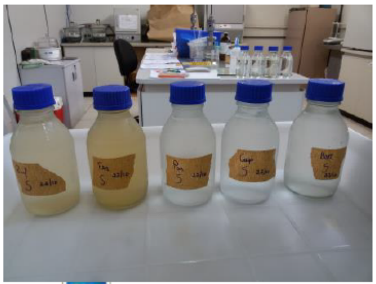


Figure 2: Variation of flow, total phosphorous, turbidity, total suspended solids and total solids during a storm event (October/18)



✓ correlation between TP, Turbidity, SST and ST with flow during a storm event.

✓ Evidence of solids and phosphorous input Good



Left : Image of samples collected at Passaúna's reservoir.

Right : Flow chart indicating the solids fractions considered during laboratory analysis (Source : APHA, 1998)

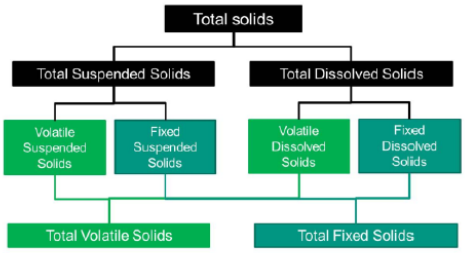
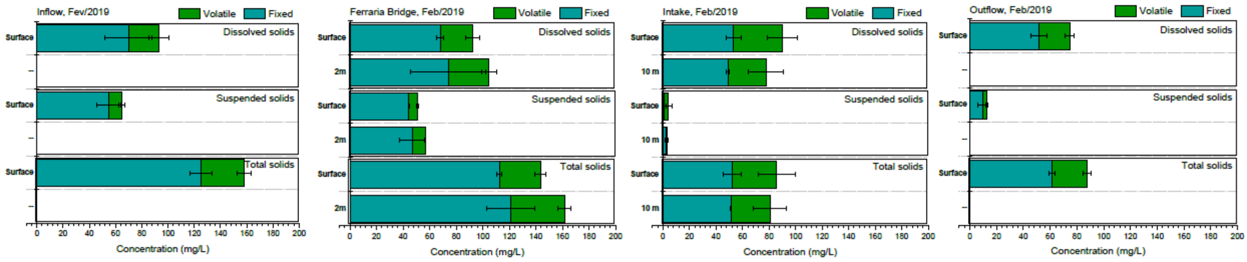
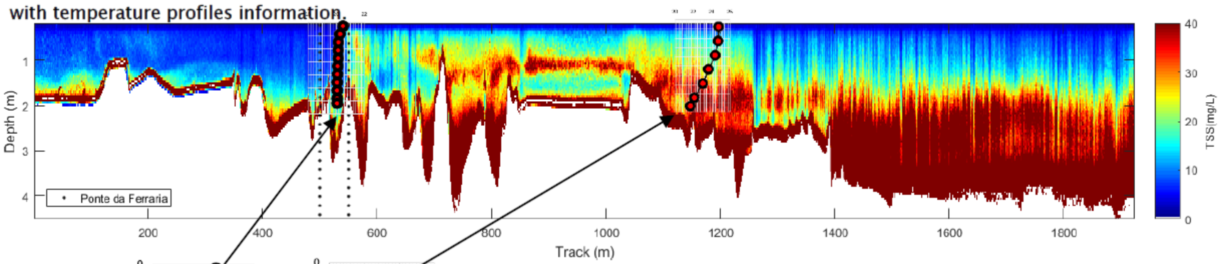


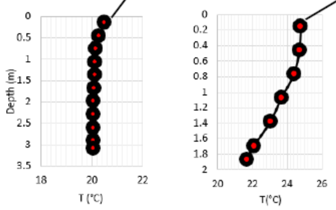
Figure 3: Variation of flow, total phosphorous, turbidity, total suspended solids and total solids during a storm event (October/18)



- ✓ Probable presence of dissolved inorganic substances due geological formation of the region (carbonate rocks)
- ✓ In average, dissolved fraction is 88% higher than the suspended fraction, with more fixed solids than volatile
- ✓ Evidence of deposition throught the reservoir (Inflow → Ferraria Bridge → Intake)

Figure 4: TSS gradient observed throughout the longitudinal transect from upstream to downstream at Passuna Reservoir, cross-checked with temperature profiles information.





- ➢ The use of the acoustic backscatter analysis indicated:
  - ➢ Good agreement between suspended solids and the corrected acoustic backscatter
  - ➢ Suspended solids spreading pattern toward the the reservoir
  - ➢ Cross-checking analysis within temperature profiles indicate a density current formation driven by temperature differences.

Innovation/Outlook

Laboratory analysis

- ➢ Turbidity as guidelines for volume used in conventional analysis
- ➢ Potential use of turbidity as a surrogate for suspended solids point quantification.
- ➢ Potential use of ADP corrected backscatter as surrogate tecnology for suspended solid mapping

Reservoir management

- ➢ Turbidity monitoring at Inflow/ Ferraria Bridge for solids evaluation:
  - ➢ Quantity/transport/ deposition during storm events.
  - ➢ Different loads due to land use modification.
  - ➢ Turbidity monitoring at Intake: water treatment operation.

Authors Heloise Knapik, Luziadne Gurski, Jullyane Oliveira, Liege Wosiacki Contact helogk@gmail.com / heloise.dhs@ufpr.br

Funded by Federal Ministry of Education and Research, BMBF Web www.mudak-wrm.kit.edu

MuDak-WRM

FONA Research for Sustainable Development BMBF

Sponsored by the Federal Ministry of Education and Research

DOM: sources, variability and insights

Evaluation of dissolved organic matter occurrence, spatial and temporal variability through spectroscopic analysis and chlorophyll-a.

Context

Dissolved organic matter (DOM) qualitative and quantitative analyzes allow a better understanding of water quality dynamics in a reservoir.

Objectives/Goals

- Identify DOM sources, variability and decay
- Evaluate DOM spatial and temporal variability
- Identify algae occurrence and variability throught space, time and depth.

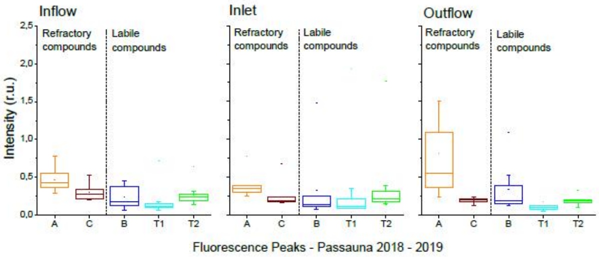
Methods

Dissolved organic carbon	Small sample volume (40 mL), membrane filtration (0,45 µm), NDIR high-temperature catalytic method (Shimadzu).
Organic matter characterizatioin	• Emission-excitation fluorescence and uv-vis absorbance spectroscopy techniques. • Small sample volume (10 mL), membrane filtration (0,45 µm). • Data treatment required for peaks identification (DOM classification).
Chlorophyll-*a*	• 3 L sample collection, dark mantainance and same day filtration. • Pigment extraction through 90% acetone with GF/C filters. • Absorbance measured at three wavelengths (664, 665, and 750 nm).

Results

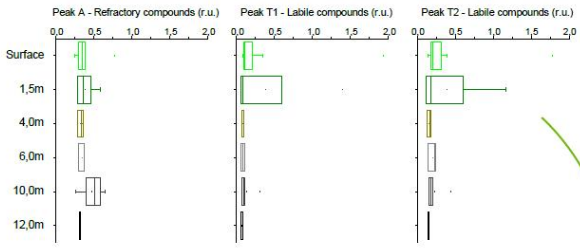
- Differentiation between **labile and refractory organic matter.**
- Ocurrence of **algae and primary production** throught the reservoir.
- Probable **algae death and sedimentation** (bottom labile DOM)

Figure 1: Variation of fluorescence peaks intensity for Inflow, Inlet and Outlet [Passaúna 20-18 -2019]

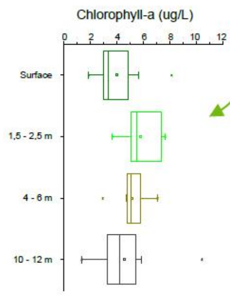


✓ Predominance of refractory compounds at Inflow (indicating pedogenic material loading) and at Outflow (humic substances from bottom layers of the reservoir)

Figure 2: Variation of peaks intensity for Inlet [Passaúna 20-18 -2019] in different depths



✓ Evidence of autochthonous production in the photic zone (higher intensity and variation of peaks T1 and T2, and presence of algae (higher concentration of chlorophyll-a)



Left : Image of Passaúna's Reservoir during a field trip (August/2018).

Right : Example excitation-emission matrix (EEM) and the identification of peaks related to different organic matter characteristics (labile and refractory).

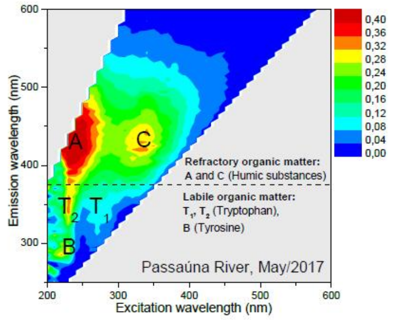
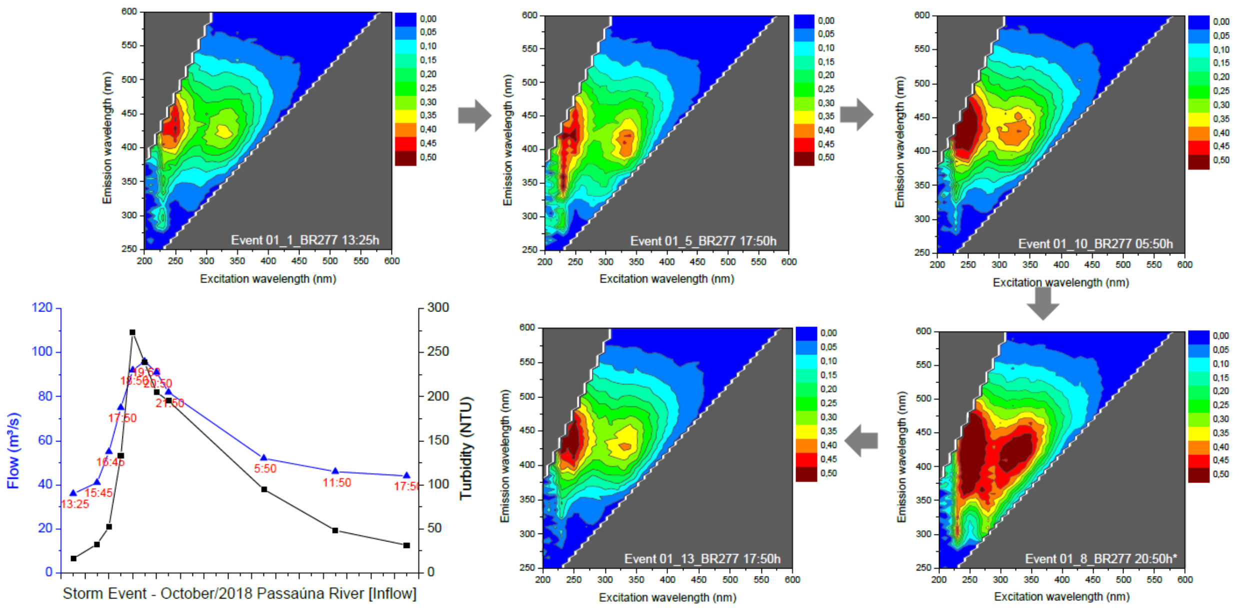
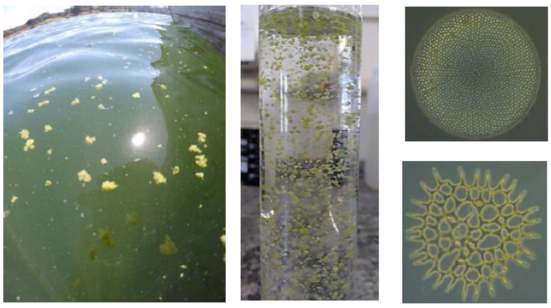


Figure 3: Variation of EEM during a storm event (October/18)



- ✓ Predominance of refractory compounds during the storm event (indicating pedogenic material loading) at Inflow.

Figure 4: Occurrence of algae at Passaúna's Reservoir



Innovation/Outlook

- ✓ Rapid organic matter sources identification (allochthonous x autochthonous x antropogenic).
- ✓ Improved information for reservoirs's operatin and management (DOM x algae occurrence x taste and odour in water).
- ✓ Potential use of DOM characteristics for in-situ probes calibration.

Authors Knapik, H.; Gurski, L.; Barreto, N.; Oliveira, J.
Contact helogk@gmail.com / heloise.dhs@ufpr.br
Funded by Federal Ministry of Education and Research, BMBF
Web www.mudak-wrm.kit.edu

5.7. Work package 7 – Data exchange and interoperability

5.7.1. Introduction and objective

The goal of Work Package 7 is the development of an information system that contextualises water quality data describing water reservoirs and their catchment areas derived from a variety of data producers. Therewith users are supported in decision making for water reservoir management.

Work Package 7 is divided into three partial objectives (Figure 74):

1. Development of a suitable data provision technique. The system shall allow for transmitting well-structured data in a way that corresponds to the technical skills of data providing users (e.g., scientists conducting measurement campaigns).
2. Development of a data pool component. The data pool shall integrate remote sensing data, in-situ sensing data, and results from domain models.
3. Development of a web client component. The web client shall allow for both, data exploration and data monitoring.

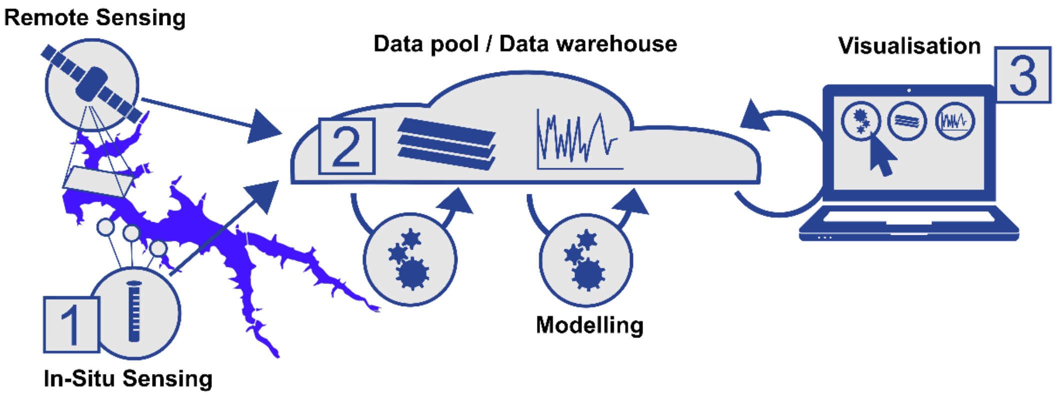


Figure 74: The objectives of the three work packages comprise (2) the setup of a central data pool, within which the used data types can be handled, (1) the integration of remote sensing and in-situ sensing data into this data pool as well as (3) the visualisation of these data types.

The foundation of the subsequently presented system architecture design was a comprehensive requirements analysis that addressed a range of core requirements categories:

- Types of data used by the partners of the consortium
- Requirements towards data management, analysis, and visualisation
- Requirements towards data formats and data access mechanisms

As a result of the analysis, it became apparent, that besides different types of sensor data (remote and in-situ), also output of models and geographic base data need to be considered. Besides these requirements towards the supported types of data, a strong emphasis was on the need to have a pragmatic approach that can be used by domain scientists in their daily work without needing comprehensive background knowledge on information technology. Consequently, it was necessary to abstract from complex underlying technologies by providing easy to use interaction patterns such as data templates or ready-to-use visualisation tools.

5.7.2. Results

5.7.2.1. System Architecture

Based on the requirements analysis and on a continuous review of the state of the art, the system architecture for the MuDak-WRM spatial research data infrastructure was developed (Figure 75). Basically, the structure of the architecture is following the functional aspects outlined in the previous section. In general, there are three main elements:

- Data ingestion: enabling the flow of information into the data infrastructure including a data ingestion module for CSV data and an approach for consuming data streams based on internet of things technologies
- Data storage and management: a relational database for storing in-situ observation data and separate approaches for storing raster data
- Data visualisation: web applications for data exploration and presentation

These different components will be introduced in more detail in the following sub-sections.

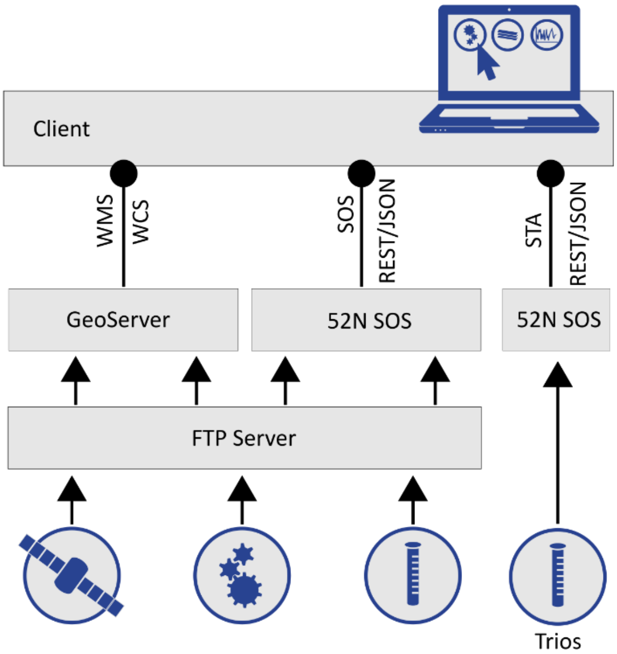


Figure 75. This figure sketches the project architecture. The data flow direction from bottom to top. The results of the three data sources remote sensing, domain models and in-situ sensing are stored on an FTP Server. In parallel an advanced data flow has been established for the automated data coming from TriOS sensors. On the service level in the centre raster data is stored on a GeoServer, in-situ data is stored on a 52°North SOS. The data is served via standardized and optimized interfaces and consumed by a client.

A fundamental cross-cutting objective of Work Package 7 is to ensure a high amount of portability, scalability, and integrity. To achieve the former two aspects, special consideration was given to the development of a containerized software architecture. A container is a standard unit of software that packages up code and all its dependencies such that the application runs quickly and reliably in one computing environment as in another[1].

[1] https://www.docker.com/resources/what-container

In order to attain the latter a reasonable usage of free open semantically rich standards for both, communication interfaces and data models is preferred. These standards include INSPIRE guidelines and specification of interfaces and data models/formats from the Geo-IT domain, such as those of the Open Geospatial Consortium (OGC) (Web Map Service, Web Feature Service, and Web Coverage Service), and techniques from the OGC Sensor Web Enablement suit (e.g., SensorThings API, Observations & Measurements).

5.7.2.2. Development of a suitable data provision technique

The project's water quality data can be divided into three categories:

- In-situ data, also referred to as ground-truth data.
- Remote sensing data.
- Data from water domain models.

In-situ data

Throughout the project's measurement campaigns a huge amount of highly diverse measurements have been taken by the project partners, to explore the water body of the Passauna water reservoir in depth. These measurements range from plain stationary time series and profile measurements to measurement transects taken with mobile sensor platforms such as the catamaran deployed in the project.

Although there are best practice methods from the Sensor Web Enablement and the Open Data community to deal along with plain data formats, it was not possible to direly apply these approaches to the available data variety. There were mainly two reasons for this: On the one hand, the underlying IT standards have a rather high complexity, so that these approaches should not be directly exposed to users. Instead, an encapsulation that focuses on the important information for the specific domain is needed. On the other hand, the data used in the project had requirements that go beyond the standards baseline (e.g., specific consideration of measurement campaigns, supporting different types of measurements), so that extensions and profiling of the existing technologies were needed.

In order to determine a data provision workflow, the composition of the project consortium and the way data acquisition is usually performed within the water quality domain has to be considered. Most of the project's data is collected by a large group of Master and PhD students, either by taking manual specimen or maintaining specialized measuring instruments. The collected data is then stored in CSV-files[2] on a file system for further analysis. These CSV-files neither do follow any formatting guidelines nor do they provide any metadata information about the measured data despite the measurement time and an id of the measurement spot. Merely a minor group of the project's data providers have a dedicated background on data acquisition technologies (e.g., TriOS). Their data provision techniques are flexible and they can easily adopt a committed project guideline. The project's data provision schema has been designed to minimize the obstacles for the majority of data providers in this project (i.e., the PhD students) in order to maximize the data contribution.

Within Work Package 7 we introduced a common way for providing the collected scientific observation data. This was formally specified as a template-based approach, which one hand defines a hierarchical data organisation (folder structure and file name conventions). On the other hand, it specifies the structure of the observation data and their corresponding metadata. The resulting formal CSV template is described in further detail in the next sub-section.

[2] Character Separated Values in plain text files.

The resulting data files can be interpreted by a synchronisation algorithm and their content can be automatically fed into the data pool. Figure 76 sketches this workflow.

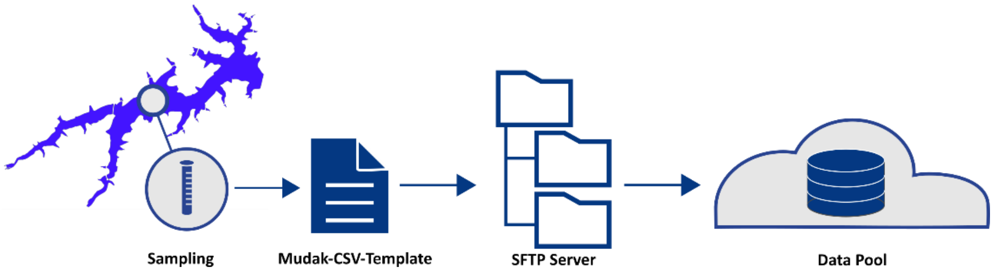


Figure 76: This figure sketches the data flow for manual in-situ observations. The samplings are translated into a CSV file according to the projects' guidelines and stored on an SFTP-Server. Then the data is automatically synchronized with a database in the projects' data pool.

The consortium decided to use a plain FTP-Server to store the structured files. This server has not been rented in an external cloud environment but provided by the project partner KIT. This ensures the long-term storage of the project raw data and data availability is not dependent on the projects' financial resources.

A CSV-template for in-situ measurements within the water domain

In order to facilitate the provision and integration of data collected by the scientists working in the project, it was necessary to provide a common and pragmatic workflow which can be applied to all data collected in the project. This way, several important goals can be achieved:

- Provide a human-understandable/readable format for the collected observation data
- Provide a data format that can be automatically processed in order to ingest collected data into the data pool
- Ensure applicability to all types of data used in the project
- Ensure that a minimum set of metadata is provided in order to identify, interpret, and discover the ingested data sets
- Hide the terminology of the more complex underlying IT standards

To address these requirements, an approach based on a CSV-file template was used. Besides the motivation presented before, this solution offers further benefits because CSV structures are familiar to many scientists and because the creation of data files following a CSV schema is rather straightforward to that in implementation in many scientific tools becomes possible.

In what follows the template is detailed, because it is a fundamental component for the project MuDak-WRM. The well-defined template closes the gap between the original data handling process of the project partners and an integrated and harmonized data provision approach with minimized effort for the data providers.

The first section of the template definition describes how to store the generated CSV-files. For each of the two project study areas, the Große Dhünn-Talsperre and the Passauna reservoir, a root folder is provided. Within this folder a designated folder for each project partner has been created. Which results in the following pattern:

- /01_Grosse-Dhuenn-TS/09_SensorWeb_InSitu_Data/<PRODUCER>/
- /02_Passauna/09_SensorWeb_InSitu_Data/<PRODUCER>/

Uploaded files follow a naming convention, which eases the interpretation for human readers:

- File name pattern: <reservoir_id>_YYYY-MM-DD_<instrument_id>#No.csv

- Example: PAS_2018-04-24_U-50PC#1.csv

The second section of the template definition specifies the metadata and observations data sections. The metadata section consists of a set of attributes giving a context to the observation data listed in Table 9.

Table 9: Metadata attributes of the template

EQUIPMENT	Used equipment for data collection.
PRODUCER	Organization that produced the data.
CONTACT_EMAIL	Email address to contact in case of questions.
AUTOMATIC	TRUE: automatically generated data (e.g., by a sensor which autonomously generates data files). FALSE: higher amount of human interaction was necessary (e.g., analysis of a sample or human reading of a scale on a sensing device).
TIMEZONE	Time zone of date and time.
VERTICAL_ORIGIN	Origin of profile samplings, e.g., WATER_SURFACE or GROUND_SURFACE.
VERTICAL_DIRECTION	Either depth or height
COMMENT	Any comments to this dataset

Within the same file the observation data is structured in a table containing the following attributes described in Table 10.

Table 10: Observation structure of the template

SITE_ID	The id of the site, the measurements have been taken. Measurements with the same site id are grouped together
WGS84_LAT	Latitude of the measurement. These coordinates can change for the same site_id. The coordinates are given in decimal degrees and WGS 84. An accuracy of 7 digits is sufficient.
WGS84_LON	Longitude of the measurement. These coordinates can change for the same site_id. The coordinates are given in decimal degrees and WGS 84. An accuracy of 7 digits is sufficient.
DATE	Encoded as YYYY-MM-DD, e.g. 1970-01-01
TIME	The time a measurement has been collected (not stored). If time is neither known nor important the field can be left blank.
VERTICAL (optional)	If depth/height is important and available, this column states the depth/height for each measurement related to the origin given in the meta data section. Typically this is depth from the water surface per measurement. If the

	measured values reflect an entire layer, this column states the upper border of the layer in case of depth and the lower border in case of height.
VERTICAL_TO (Optional)	If depth is important and available and the measured values reflect an entire layer/interval, this column states the ending border of the layer.

Within the next columns the measured values are listed. The according title for each column is the measured_parameter (e.g. turbidity) combined with the unit of measurement. Underscores "_" are used instead of whitespaces. The column title should be as human readable as possible. The unit of measure3 is noted with underscore and parentheses, e.g. WIND_SPEED_(m/s). In case of no unit the parenthesis should be empty, e.g. _() The LLD values should be encoded with the value of the LLD, e.g. <0.005 instead of <LLD.

Remote sensing data

The remote data flow has been established similar to the in-situ dataflow. Remote data is usually provided in raster data formats. The project team consortium has decided to store raster-based data in the GeoTIFF format. GeoTIFF is an OGC standard[3] and widely used in Digital Geography. Due to the characteristics of these data type, a guideline for the internal file structure is not necessary. Satellite based remote sensing data allows to derive a temporal series of scenes rather than a single standalone scene. Thus, multiple GeoTIFFs files form a raster data series. Analogous to the in-situ data provision template a guideline document was created, which details a folder hierarchy pattern and a naming convention for the data files.

The folder hierarchy and the file name patterns define the necessary attributes to synchronize the file set with the data pool:

Folder hierarchy pattern:

/02_Passauna/09_SensorWeb_Raster_Data/<PRODUCER>/<PARAM>/<FILE>

File name pattern:

<TIMEINTERVAL>_<RESOLUTION>_<PROJECTION>.tif

Example:

2018-01-01P1M_60m_32722.tif

Herewith, additional metadata files for a raster data series are not needed. The attributes and their meaning are listed in Table 11.

Table 11: Attributes and meaning

PRODUCER	Data providing organization
PARAM	Observed parameter. In UPPER_CASE_AND_UNDERSCORE Examples: LANDUSE, ORTHOPHOTOS, NDVI

[3] The units specification should follow the Unified Code for Units of Measure (the UCUM: https://en.wikipedia.org/wiki/Unified_Code_for_Units_of_Measure) is a system of codes for unambiguously representing measurement units to both humans and machines.

TIMEINTERVAL	The time interval for which the data is representative for.
RESOLUTION	Spatial resolution of each pixel.
PROJECTION	The numerical EPSG code defining the coordinate reference system that is used

Data from water domain models

The different kinds of models within the project to use both, in-situ and remote sensing data as input parameters. However, the results of the water domain models are also time series or raster series data. Thus, there is no additional guideline necessary for the model results. The data providers will either follow the guidelines for in-situ data or for remote sensing data.

Approaches for Importing In-Situ Data from Different Sources

In order to enable the loading of in-situ data that is available via the previously described template, a dedicated data loading module was developed as part of the project. Starting point of this development was the 52°North SOS Importer which was subsequently enhanced to handle the CSV template that was developed in cooperation with the project partners. Important functionalities offered by this extension include:

- Support to handle profiles measured along the z-axis (e.g., water temperature in different depths)
- Support to handle spectral measurements
- Support to handle feature hierarchies (e.g., enable the association between measurement locations and the corresponding water body or catchment)
- Support to handle further additional (metadata) parameters in the measurement data (provided as so-called O&M parameters)

Complementary to this pull-based import process, also push-based data delivery methods were explored. Especially for the sensor hardware provided by TriOS a prototypical approach was achieved to link existing sensors via the MQTT protocol (an approach from the Internet of Things community) to a Sensor Web server using the OGC SensorThings API specification. This push-based approach has shown the potential to reduce latencies due to an active delivery of data instead of periodical data polling.

5.7.2.3. Development of a data pool component

The previous section has described how the data has been structured in a folder hierarchy manner so that the data files can be read by import algorithms and fed into the data pool component. This section is about the architecture of the data pool. The data pool consists of two modules. One module stores and manages the project’s in-situ data series, the second part does the same for the project’s raster data series.

Data Pool Module for In-Situ data

Best practices for the management and integration of plain time series data are well described for example by the OGC Sensor Web Enablement community. The OGC has introduced the Sensor Observation Service (SOS)[4] as a standard more than ten years ago. The SOS is a web interface for communicating sensor-based time series. In 2016 the concept has been refined

[4] https://www.ogc.org/standards/sos

with a focus on plain data streams in an Internet of Things context by the OGC SensorThings API[5].

Best practices for complex in-situ measurements, however, are described vague. In the past the project partners 52°North and the Wupperverband have iteratively developed a harmonized relational data model which is based on the data models proposed in the OGC SOS and the OGC SensorThings API standards. This data model is capable of storing plain time series data in an effective way (Figure 77).

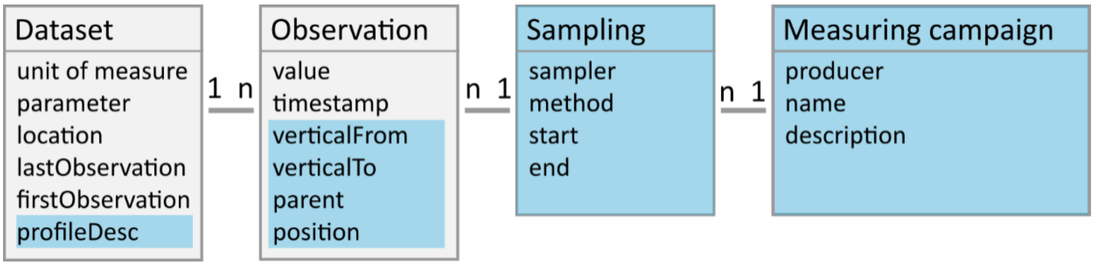


Figure 77: This figure show the main classes of the optimized data base schema realized in the Sensor Web infrastructure of the Wupperverband. During the project this data base schema has been extended to allow for modelling of more complex measurements. The extensions are highlighted in blue.

A measurement profile, e.g. a buoy with depth measurements, is described by a fixed horizontal location. It consists of a set of child measurements, each taken at the same or different timestamps. Thus, a vertical dimension was added to the Observation object. Since also vertical layers are measured, e.g. by sediment cores it is possible to add two vertical depth to an observation. All child observations refer to a parent observation.

A measurement trajectory, e.g. the result of a measuring boat action, is characterized by a composition of observations that differ in their location. Therefore, the attribute position has been added to the Observation object.

Samplings are usually water probes, which are analysed in a laboratory to retrieve a couple of chemical parameters about the water quality. These probes can be taken once, or even regularly at the same spot. These aspect needs the introduction of a further composition of observations. Whilst the Dataset object composes Observations with the same measuring parameter and unit, a Sampling object bundles a water probe at a certain point in time but with the resulting number of measure parameters. Samplings can be organized in measuring campaigns, as performed within the MuDak project.

In order to handle these requirements, the 52°North Sensor Web Server was used. This includes on the one hand support for the OGC Sensor Observation Service standards and on the other hand an implementation of the OGC SensorThings API specification. However, in order to fulfil the needs of the MuDak-WRM partners and use cases, extensions were necessary in order to handle the specific concepts outlined in the previous paragraphs. For this purpose, especially the following extensions were implemented and evaluated as part of the project:

- Extension to handle incoming data from the TriOS sensors
- Enhancement of the data model and data management layers to handle
    - Profile measurements
    - Measurements taken along transects

[5] http://docs.opengeospatial.org/is/15-078r6/15-078r6.html

- Samplings
- Measurement campaigns

Further work besides these extensions comprised the evaluation of options for cloud-based deployments as well as basic mechanism for controlling the access to the data (i.e., limit the access only to project partners).

Data Pool Module for Raster data

Earth Observation (EO) datasets commonly provide scenes for particular regions of the Earth's surface. Each scene consists of multiple raster satellite images representing the space at individual time stamps. A key challenge in managing EO datasets is providing fast access to 2-dimensional coverages periodically collected. A representation concept of multi-dimensional space-time arrays and an approach for providing dynamic and on-demand delivery of 3-dimensional subsets, increases the interoperability and usability for EO datasets. A special scenario of sub-setting is the extraction of a time series of single pixel. This is important for a detailed analysis or visualisation and comparison with in-situ measurements. In the course of the project, two different approaches to organize and store raster data have been evaluated by 52°North. An additional approach has been explored within a cooperation with the Institute for Geoinformatics of the University of Münster.

The first approach (Figure 78) is based on the community version of the general-purpose array data base SciDB (https://github.com/Paradigm4/SciDB), and a prototypical extension for OGC Web Coverage and Web Map Services has been developed. The core of the web services was an OGC Web Processing Service with a single interface to the SciDB data base which has been proxied by dedicated WMS and WCS endpoints. This reduces the need to develop several interfaces between the different web services and the database and is easily extendable to also provide for instance access to averages and other data products directly from the database possibly reducing the communication overhead.

Two-dimensional gridded pixel data sets are extracted from individual satellite images of single time stamps and insert into a 3-dimensional space-time array based on SciDB. On arrival of a new satellite image or product, its pixel data is transformed into a 2-dimensional SciDB binary-file and pushed on top of the present array. Metadata, such as timestamps and scales of the pixel values, are persisted in an additional file-based database. Standardized access to the data is facilitated via Web Coverage and Web Map Services (WCS and WMS by the OGC). Common output formats are supported for geo-spatio-temporal datasets such as netCDF and GeoTIFF. While the WCS interface provides access to the raw data used in subsequent models and analyses, the WMS provides styled images that can easily be added to map clients.

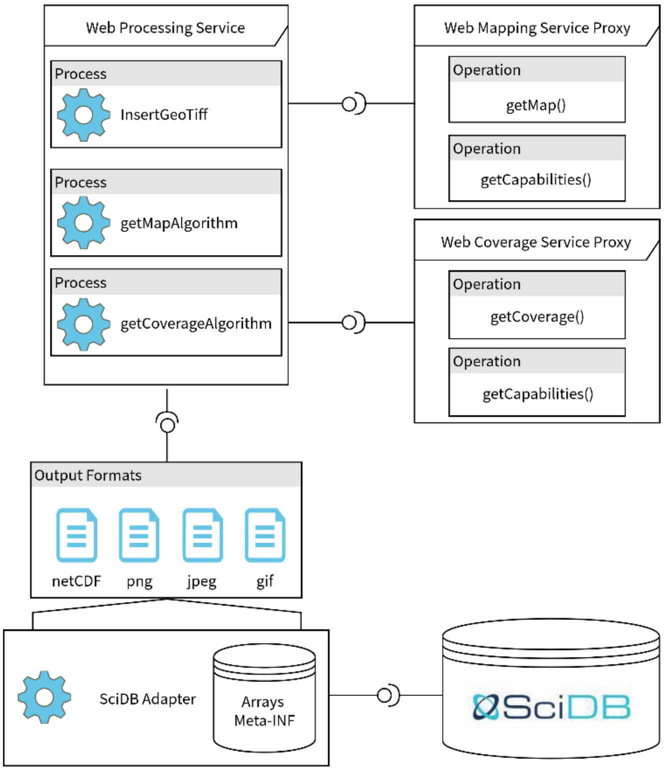


Figure 78: Overview of the components extending the community version of SciDB with OGC web services (WMS and WCS through a WPS). Only the WPS interacts with the data source through a SciDB-adapter which also organises the meta information (e.g., coordinate and temporal reference systems). The WMS and WCS proxies only translate dedicated WMS or WCS request into corresponding WPS processes to serve client.

The second approach is based on the GeoServer[6], an open source implementation providing data access to a large variety of geo data sources. The GeoServer already provides OGC services such as WCS and WMS which are essential for the project. The storage of the data is not organized in a single multidimensional array, but mainly kept file based and agnostic of the temporal domain. This eases the data integration, as new remote sensing images and products only need to be made available to the file system and registered as resources and layers in the GeoServer instance. However, the data access of time series of data is essentially based on multiple encapsulated requests iterating over the available time stamps. Tools and software components have been implemented in order to ease the data publication and access.

The third approach can be seen as a hybrid version of the two previous ones and is based on gdalcubes[7]. In gdalcubes, the data remains in a file-based storage, but the interface is aware of the multidimensional array structure across all files. This allows to conveniently access all kinds of multidimensional subsets of the data while having a simple and robust file-based structure of the input data.

During the development of the SciDB based approach, it turned out that the maintenance of the SciDB core was too time consuming while the conceptual idea to wrap the WMS and WCS around a single WPS had proven valuable. Under the given time constraints and affordance within the consortium, a switch towards the GeoServer approach was made. This switch was also motivated by the client implementation, as the client software could easily be extended

[6] geoserver.org
[7] https://github.com/appelmar/gdalcubes

towards the available web service capabilities of the GeoServer instance. The implementation of gdalcubes has been developed in parallel as an outlook on a potential future development direction beyond MuDak-WRM and hence only been compared at the very end of the project. Its downside was the lack of implementations of the necessary web services at that point. However, based on the insights from MuDak-WRM on all three approaches, the hybrid approach of gdalcubes is a powerful alternative.

Data Processing

Besides enabling the ingestion, management and access to the collected scientific observation data, it is also important to offer tools for performing processing and analysis tasks on the collected data. This could range from the determination of statistical characteristics to conducting complex analyses.

Typical tools for performing such tasks are R and Python. These are commonly used across many different scientific domains. Thus, on further objective of this work package was to simplify the integration of the collected data into such analysis tools.

For this purpose, MuDak-WRM contributed to the advancement of the sos4R[8] package which provides a library to access OGC compliant SOS servers from R. More specifically, the contribution within the MuDak-WRM project was focused on improving the usability of this package by introducing an additional abstraction layer that better hides the underlying complexity of the technical Sensor Web terminology. For example, if a scientist would like to discover information about available data sets, this abstraction layer takes care of automatically orchestrating the necessary operation calls to an SOS server. This makes it possible for scientists to use observation data in R without the need to work through very comprehensive technical documentation

In addition, further work has been conducted to evaluate first approaches to achieve similar functionality for Python.

5.7.2.4. Development of a web client component

During the requirement analysis phase the need for two partial apps was identified. One app should give a comprehensive view of the current state of the reservoirs water quality parameters. This app is realised as a dashboard. A second app should realize a catalogue in order to explore all datasets that are available within the MuDak-project and make them downloadable. The two partial apps were developed and integrated in MuDak web client.

The Dashboard App

The Dashboard View consists of a set diagrams giving an overview of the last state of the reservoir (Figure 79). In the upper left corner, a water quality index (IQA) of the reservoir is shown as a heat map chart for the last three years. The IQA is computed from both, in-situ parameters and remote sensing data, were available. The upper centre card shows the Passauna reservoir on a map. Four representative points have been chosen, two on both sides of the buffer, one within the reservoir centre and one at the dam. At these very points the corresponding remote sensing data is retrieved and plotted as four time series graphs in the upper right.

In the second row water temperature at the buffer is shown as an isopleth diagram. On the right the reservoir volume is shown as a time series graph.

[8] https://github.com/52North/sos4R

On the lower left the water temperature is shown within the reservoir centre. The lower right shows two profiles. One for salinity, the other one shows the redux potential.

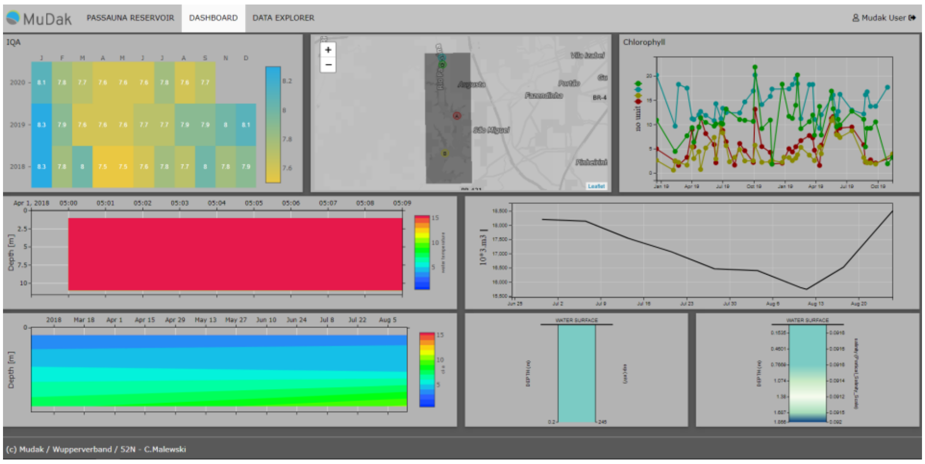


Figure 79: This figure shows a state from the Dashboard App. The dashboard app consumes the latest data from the projects' data pool and displays it according to their data type.

The Data Explorer App

The Data explorer view integrates the various data types, raster and in-situ parameters in one view and makes them searchable and findable. On the left hand side of the view there are multiple filter options ranging from the selection of the measure parameter to the producer or whether manual or automatic measurements should be shown. Also the parameters from the remote sensing datasets can be selected.

All datasets that fit to the current filter status are shown on the map and in a list below the map. The map therefore does not differentiate between the various sensing types, but displays their position, trajectory or observation area. The listed items beneath the map are interactive and display the characteristic metadata for a dataset along with a preview. The preview type is automatically generated from the data characteristic. Figure 80 shows the chlorophyll data from an in-situ sampling as an isopleth map. Figure 81 shows the attributes from the remote sensing data. A user can interactively click into the map in order to generate a time series at that very position on demand.

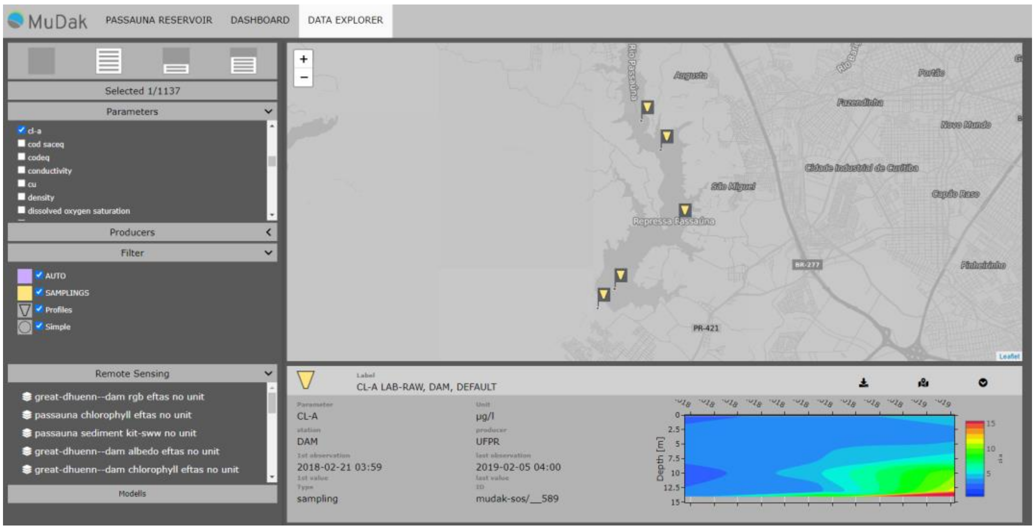


Figure 80: This figure shows the data explorer app. On the left hand side users can search the available datasets by their attributes. The main view shows the datasets positions on a map and their preview in a list.

Figure 81: This figure shows another state of the data explorer app. The main view shows a selected dataset from a satellite. It offers a user further analysis functionality and a data download.

To support the development of the of the presented web viewer, the open source framework “Helgoland Toolbox”[9] of 52°North was used as a baseline. This framework offers a broad range of building blocks in order to facilitate the creation of web applications for exploring and visualising observation data in spatial data infrastructures. However, based on the results of the requirements analysis and the practical work in the project, it was necessary to develop a range of extensions and adjustments. This comprised especially the following aspects:

- Handling of profile measurements
- Handling of measurements taken along transects (e.g., measurements taken from a boat)

[9] https://github.com/52North/helgoland-toolbox

- Development and implementation of an approach for handling spectral data
- Ensure that ongoing technological developments are incorporated to increase the robustness of the application (e.g., new versions of core libraries)
- Support of measurement campaigns
- Support of samplings
- Evaluation of support for the OGC SensorThings API specification

6. Minimum Monitoring Concept for drinking water reservoirs

The concept of minimum monitoring is a joint result from all work packages of the MuDak project, and therefore presented at the end of the results section.

For many reservoir operators it is a complicated task to define the ecological (trophic)- and functional status of their reservoir. This might be especially the case, if the reservoir has been operated for many years to decades in which no environmental data was acquired or the assessment methods changed and available data might not be consistent. E.g. the base maps used for the calculation of the initial volume might be imprecise or corrupted or even the gauging station (discharge) data might be biased, leading to erroneous data sets. In some cases, the trophic status of the water body might be unknown and needs to be assessed to adapt water treatment and protection measures.

It might be even more complicated to make predictions for the future status of the water body. An optimized monitoring including a plausibilisation of the data will increase the confidence into predictions and consequently to take measures before it is too late and costs may rise significantly.

The minimum monitoring aims for two main objectives:

1. A cost reduction caused by the monitoring efforts, which need to be taken to keep full control on the processes in- and around the reservoir.
2. Long-term plausibilisation of collected data. An optimal monitoring should allow the operator to use collected data to confirm the correctness between compartments (catchment, river, water body) to create the confidence in the data to predict processes (e.g. eutrophication or siltation) in the future and to plan accordingly with necessary resources for measures.

Pre-requisites to implement a minimum monitoring strategy

Before the minimum monitoring can be implemented, for each relevant compartment to the reservoir, information needs to be collected and fundamental processes assessed. It might be the case that the status of one reservoir is already critical (showing symptoms like dead fish, algae blooms, etc.) in terms of eutrophication or siltation. In that case immediate measures need to be planned. The minimum monitoring can only be implemented if the status is still oligo- to mesotrophic. Otherwise, the causes for the bad water quality need to be investigated and measures taken. Only after a stabilization of the water quality status a minimum monitoring can be started (Figure 82).

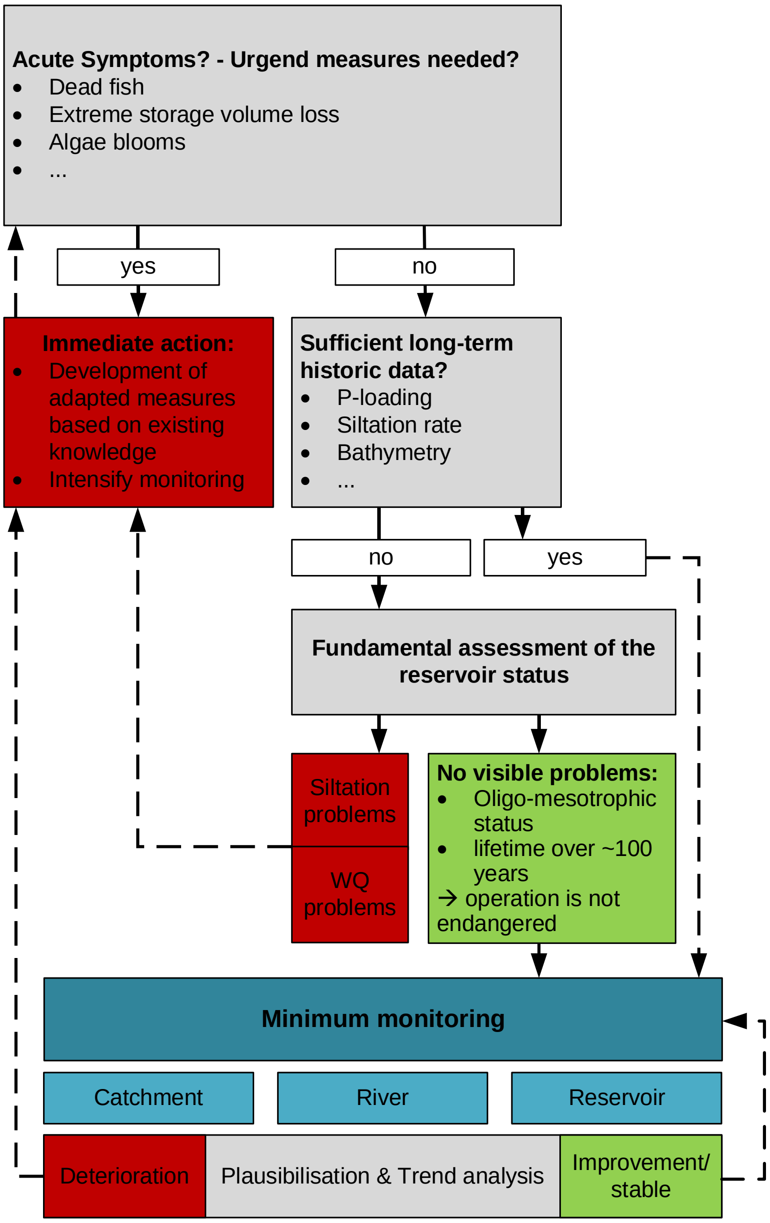


Figure 82: Structural overview graph of the monitoring approach.

Necessary information to implement the minimum monitoring:

1. Main processes in the catchment related to erosion are well understood. E.g. main delivery areas have been identified. Relation between precipitation/flood events and sediment/P – input have been investigated and defined.
2. Long-term data of the river discharge is available to define low-flow, mean flow and high flow phases and to create a cumulative discharge distribution curve.
3. A full assessment of the reservoir itself has been conducted. This should include the actual water level-volume curve based on a detailed bathymetric survey (see Flyer in chapter 5.1.3), a precise assessment of the sedimentation rate (t/a), if possible the distribution of the sediment on the lakebed. The Phosphorous stock in the water column and in the sediment needs to be defined. The annual P-loading kg/m³ into the reservoir must be calculated to have a measure for the tendency in the future.

The minimum monitoring:

The monitoring concept aims to reduce the efforts and costs of the continuous control of critical water quality and further environmental parameters. It should allow for the calculation and assessment of the current WQ-status as well as to predict the status in the mid-term future (1-10 years). Therefore, the presented concept needs to be implemented over several years to create an adequate data basis for such interpretations and predictions.

The monitoring is split into three parts catchment, river and reservoir (Figure 83). The catchment represents the general source of most nutrients and sediment, which are transported into the reservoir over time. The temporal delay of diffuse sources is weeks to years. The river monitoring itself serves as a control for the modeled input from the catchment on the one side, and for the plausibilisation of the siltation rate based on bathymetric measurements or sediment investigations, on the other side. The monitoring within the reservoir should be able to indicate changes of fundamental parameters over time. These encompass the temperature, oxygen concentration (epi- and hypolimnion), stratification days and chlorophyll concentration. The phosphorous concentration in the water column may be highly misleading in carbonate- or iron-buffered systems, were the concentration of plant- and plankton-available P is not necessarily linked to the P-loading coming into the reservoir.

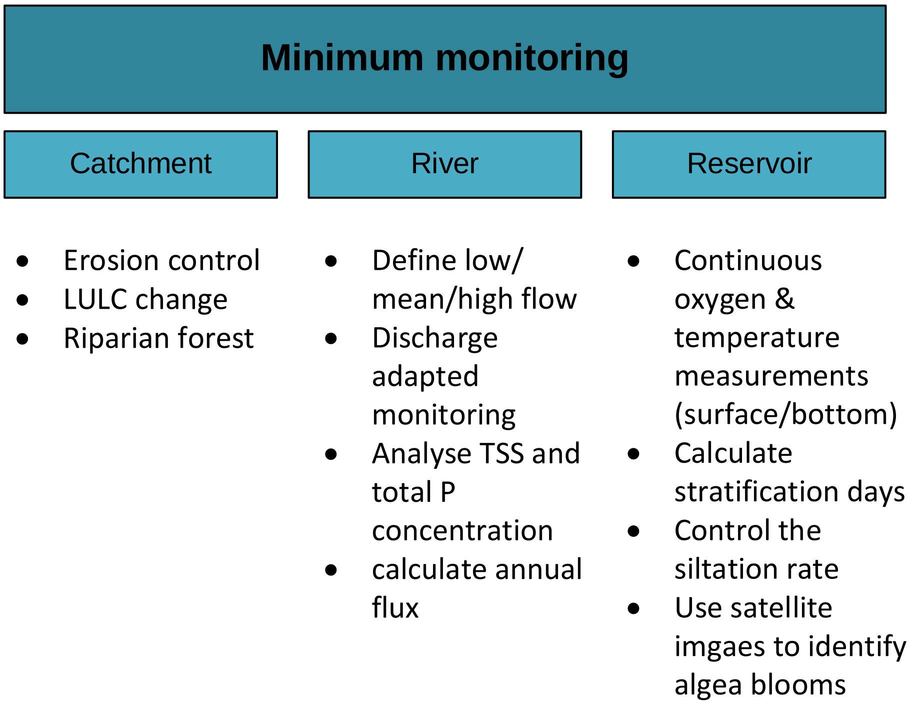


Figure 83: Overview of monitoring components in the catchment, river or insinde the reservoir.

The catchment:

If the reservoir is to be protected over many years, than the active management and control of flux-related processes in the catchment are essential. Since the extraction of relevant parameters from multispectral satellite data can be automatized, the assessment of changes (e.g. deforestation) within the catchment can be supervised with comparatively small effort and measures can be applied (e.g. reforestation) where the produce best effects.

Even though the detection of land use and land cover classes as well as the modeling of sediment input from a catchment into a reservoir might be technically sophisticated, it is possible to do so from any point of the world for any catchment. Which means, that reservoir operators or authorities can assign this task to specialists or can solve it in house.

We need to emphasize, that the long-term supervision of catchment-related processes is key to the management of the water quality in the receiving reservoir. Since the processes in the catchment may only be visible over longer time periods (> 1 year), control periods of 3-5 years seem useful, giving the analyst the chance to detect significant changes.

However, even though the intervals between subsequent assessments can be longer, it is strongly recommended to base the assessment on as many satellite images as possible. This is essential to account for seasonal effects (e.g. changes in vegetation cover (NDVI)) and allow for the comparison between different years. A resolution of one month for the erosion modelling and also to compare further parameters like land use should be obtained.

To detect trends in the catchment the comparison of the following parameters over time is useful:

- Share of bare soil
- Share of agricultural land
- Urban area
- Extent of riparian forest strips

RUSLE-based erosion modeling approaches have shown be able to reproduce the general erosion behavior in the catchment. Even though, the calculated total amount of sediment flux might deviate from the reality, the tendency over years can be assessed. Additionally, hot spots can be identified for the optimal implementation of mitigation measures. A recommendation for all actors in the catchment is, to focus on the hotspot areas first. Like this budgets can be bundled and positive examples can be created with relatively small efforts.

The river:

For a cost-efficient long-term monitoring of sediment and nutrient loads in rivers, “When” and “How often” are the most critical questions.

Nowadays, real-time online highly time resolved monitoring data can be available, however, might be limited by several aspects. First, these installations (sondes) are very costly, some need infrastructure (electricity, internet connection) and may be subject to vandalism or theft. Consequently, the permanent installation of these systems is not promising at many locations around the world. Additionally, the large amount of data can be a challenge for technicians or operators to process and extract the right information for management. The focus for many reservoirs is to control the incoming sediment and Phosphorous load. Probes for suspended matter or turbidity often have the constriction, that they provide either a low or a high measurement sensitivity. Real-time Phosphorous measurement equipment is available, but still very costly and not widely used. Therefore, the state of the art measurement installations may not be of great help for reservoir water quality management under several circumstances.

Still the problem prevails that, the main fluxes into the reservoir can easily be missed by traditional grab sampling (matter of hours) and consequently the monitoring needs to be adapted. The distribution curve of discharge over the exceeding probability through the year is an essential tool to allow for planning of monitoring action. Discharge should be split into three categories (Figure 84).

- Low-flow conditions (90% exceeding probability), were sediment load is at its minimum, point sources (WWTPs) are at their relative maximum
- Mean-flow conditions, which cover ~80% of the discharge days of the year, but do not include larger flood events
- Flood events (10% of highest discharge), high sediment loads are expected and peaks of particle bound nutrients and pollutants are introduced to the reservoir

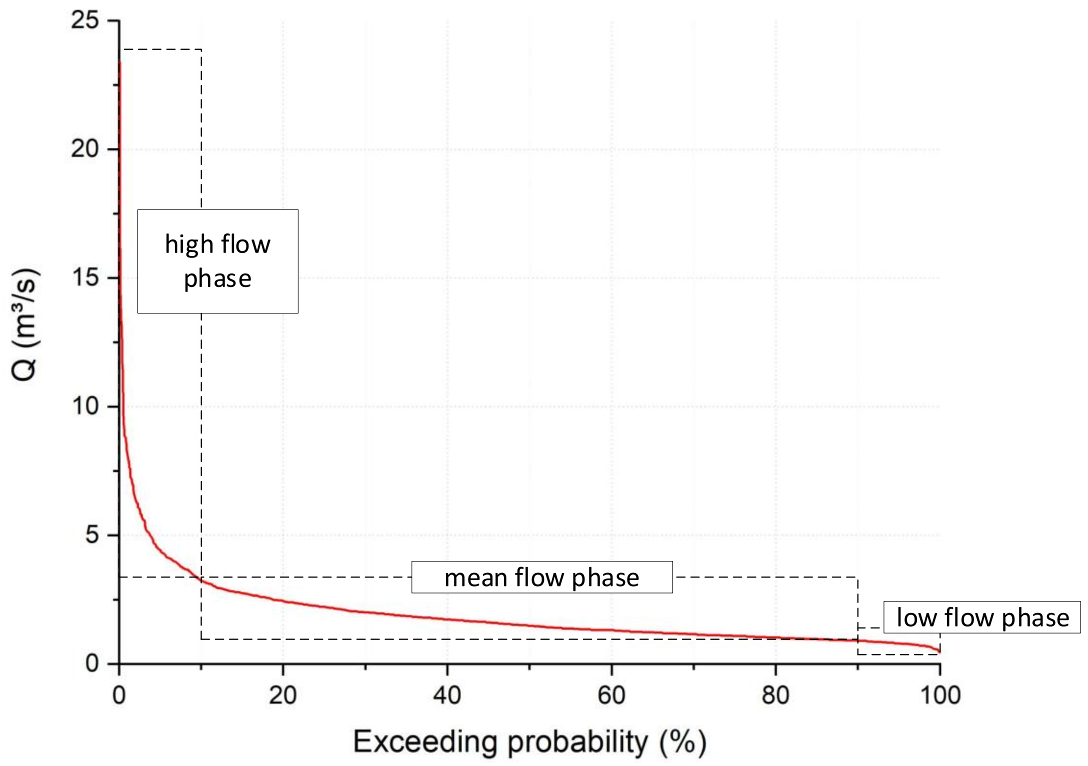


Figure 84: Exceeding probability of different discharges, example of the Passaúna River

Due to the higher probability to sample during mean flow conditions, this phase is over represented in most data sets due to inflexible monitoring strategies. For a robust calculation of river loads, all three discharge phases should be represented. Within the perspective of a long-term data set all three phases should include data from all seasons (spring to winter or dry to wet season). However, for the correct assessment of sediment and particle-bound nutrients the sampling during high flow conditions is crucial and more important than the low-flow conditions.

For the adapted monitoring, it is important, that the institution in charge is able to adapt the sampling depending on the weather and flow conditions. If a high flow phase is predicted, than an explicit sampling should be conducted, if high flow data is still missing in the data set. The conditions of the rivers should be over watched permanently by online gauging stations. It is more useful to take some samples at distinct moments than taking many samples during mean flow conditions. It can be expected, that once the data set reaches a certain number of samples, effects of e.g. hysteresis might become neglect able over time for the overall flux calculation.

The reservoir:

In order to reduce the costs and efforts of the monitoring in the reservoir the number of measurement points and water quality parameters needs to be reduced. To optimize the gained information for the reservoir management, we suggest a two-layered approach. The most important part is the analysis of the in-situ water quality, including vertical long-term information. The second part can be the satellite-based detection of changes in the reservoir water quality at the surface (Figure 85).

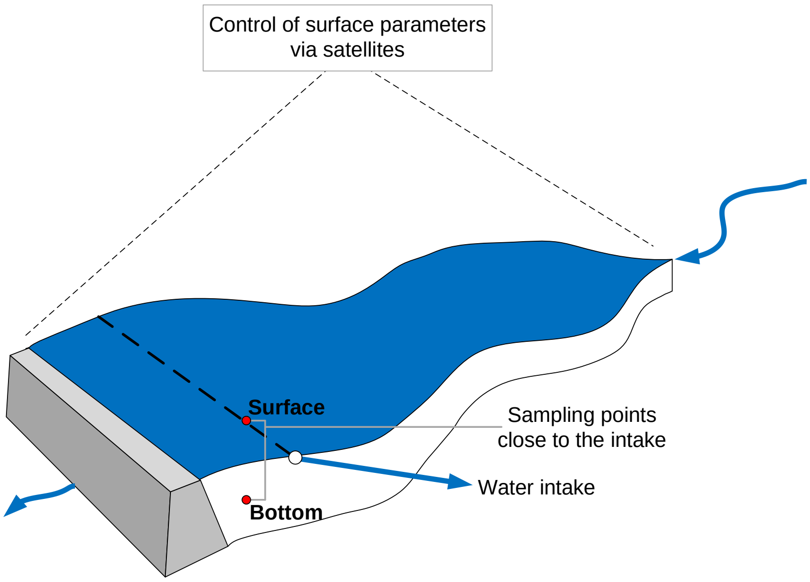


Figure 85: Schematic overview graph of the monitoring concept in the reservoir.

As illustrated in the overview graph (Figure 82) the minimum monitoring can only be applied, if no acute symptoms of deteriorated water quality are evident. The central aspect of the minimum monitoring inside the reservoir is, in contrast to other monitoring approaches, that we suggest a continuous monitoring instead or in addition to the often conducted monthly or three-monthly grab sampling campaigns. In this way, it is possible to derive the actual status, but also the long-term trend of the water quality. The detection of mid- to long-term trends can be masked by short single events/moments (floods, storms, water level changes) or seasonal effects. The most critical point is the water quality at the water intake. Therefore, we suggest to continuously controlling the WQ here. However, the sampling point should still be representative. If this is not the case (e.g. at the shore or in a shallow part of the reservoir), the next deepest point should be chosen from the bathymetric map to include the full water column in the monitoring. If the reservoir is divided in larger, important subunits, then a second location might be necessary.

We emphasize the continuous monitoring of temperature and oxygen inside the lake. They are cheap to measure, deliver fundamental information for hydrodynamic and biological process understanding and can be used as early warning parameters. If they stay in a suitable range, problems associated with toxic conditions and associated compounds, including ammonia, sulfide, manganese, and metal compounds can be limited.

For the assessment of temperature, oxygen and stratification days, temperature-oxygen loggers should be permanently installed. One, 1 m below the surface and one logger ca. 1 m above the sediment water interface. The position should be hold, independent from water level fluctuations. A measurement interval of 20 min. is sufficient for detailed interpretations of the data and still allows for maintenance intervals of ca. 6 month.

For the investigation of water quality parameters at the surface multispectral satellites can be used. Satellites like the Sentinel 2 deliver free-to-use data, which allows for the derivation of chlorophyll and turbidity values. Especially important, is the short interval between satellite flyovers, creating a dense database even in often clouded tropical or sub-tropical environments. Since most operators or authorities do not have the capacity for in-house data analysis, the online data pool gives the chance to contract companies every e.g. 3 years to analyze the development of the surface water quality.

7. Outlook and Future Research

Scientific:

The major scientific findings are expressed by the listed publications (chapter 8).

However, the following points represent staring points for further research and improvement:

- Within the erosion, modeling the channel and gully erosion was not included and may be an important reason for the deviation between the modelled sediment input and measured sediment mass. Future research should implement all types of erosion to better reflect erosion processes in order to model detailed siltation rates.

- Automatized satellite-based land use and land cover detection needs to be adapted other climate zones like Mediterranean areas to produce fully correct data sets.

- The internal phosphorous loading was addressed as a side topic within the MuDak project. In future research, it may play a more prominent role to be included in the modeling of lake processes and management strategies. The influence of changing lake conditions is still an open topic to be connected to management options.

- With respect to the UAS-based remote sensing system, more research is needed in the area of sun and sky glint reduction methods to fully correct the residual artefacts. These issues could be approached by extension of this system with a second camera taking images of the sky to correct especially reflected clouds on the water surface.

- The comparison of data acquired with the hyperspectral camera and satellite-based observations show consistent results. This enables further innovative approaches to build easy to use methods for training machine-learning models using only few in-situ measurements and water samples.

Application:

The produced results and products (Flyers) cover a wide range of topics, which can be directly transferred or applied in other catchments and reservoirs.

The approaches can be seen as blueprints to investigate certain phenomena in other locations and they show what to expect in terms of data or information output. Additionally, they illustrate the amount of expertise, effort and time as well as budget to be calculated for a reservoir operator to obtain comparable data. The high complexity of a reservoir system in terms of eutrophication and water quality makes a proper management still a challenging task, especially, if the catchment sees high usage pressure from various direction.

We developed a guideline to plan and conduct an optimal sediment assessment campaign. This can be used by any operator or authority to first create a profound database of so far uncharted reservoir bottom and sediment. It could also be used to update critical information as siltation rate, lifetime of the reservoir and location of the sediment. This information are essential for the actual assessment of the reservoir status and future measures planning.

The MuDak-WRM project not only laid the foundation to transfer the developed methods to further reservoirs, it also allows to directly transferring the results to the Piraquara 2 reservoir in the direct vicinity in the east of Curitiba city.
We hope the joint research vessel will facilitate many research campaigns for Sanepar in close cooperation with the university researchers and may lead to additional future insights for reservoir management.

In addition to the water management results, the Sensor Web can be migrated to Brazilian servers and can be used in the future to further manage reservoir-related data. It will be a good possibility to include all measurements from the catchment and the reservoir itself, based on the data compatibility table. Therefore, all data can be available and usable with a long-term perspective.

Furthermore, the evolution of the developed research data infrastructure should include the consideration of emerging developments such as the standards of the OGC API suite of standards as well as further consideration of IoT (Internet of Things) technologies and the integration of data from industrial interfaces to sensing systems.

8. Publications from the MuDak-WRM project:

No.	Author(s)	Year	Title	Journal/Location	Format	WP
1	Marcon, L.; Bleninger, T.; Männich, M.; Hilgert, S.	2019	High-frequency measurements of gas ebullition in a Brazilian subtropical reservoir—identification of relevant triggers and seasonal patterns.	Environmental monitoring and assessment, 191:357,	Article	WP1
2	Hilgert, S.; Sotiri, K.; Marcon, L.; Liu, L.; Bleninger, T.; Mannich, M.; Fuchs, S.	2019	Resolving spatial heterogeneities of methane ebullition flux from a Brazilian Reservoir by combining hydro-acoustic measurements with methane production potential.	38th International Association of Hydro Resources World Congress, Panama City, Panama	Article, Presentation	WP1
3	Hilgert, S.; Sotiri, K.; Fuchs, S.	2019	Advanced Assessment of sediment characteristics based on rheological and hydro-acoustic measurements in a Brazilian reservoir.	38th International Association of Hydro Resources World Congress, Panama City, Panama	Article, Presentation	WP1
4	Sotiri, K.; Hilgert, S.; Fuchs, S.	2019	erivation of a hydro-acoustic sediment classification methodology from an extensive dataset of six reservoirs.	38th International Association of Hydro Resources World Congress, Panama City, Panama	Article, Presentation	WP1
5	Sotiri, K.; Hilgert, S.; Gorochocki, P.; Wagner, A.; Duraes, M.; Drummond, S.; Kishi, R.; Fuchs, S.; Scheer, M.	2019	Understanding sediment transport processes – coupling erosion with reservoir siltation	11th Symposium for European Freshwater sciences, Zagreb, Croatia	Presentation	WP1
6	Sotiri, K.; Hilgert, S.; Zhang, Ch.; da Silva Santos, L.; Fuchs, S.	2019	Evaluation of two different modeling approaches for erosion and sediment input assessment	9th International conference of the European Society for Soil Conservation. Tirana, Albania	Presentation	WP1
7	Sotiri, K.; Hilgert, S.; Fuchs, S.	2019	Sediment classification in a Brazilian reservoir: Pros and cons of parametric low frequencies	Advances in Oceanography and Limnology, 2019; 10(1): 1-14.	Article	WP1
8	Fuchs, S.; Hilgert, S.; Sotiri, K.; Wagner, A.; Ishikawa, M.; Kern, J.; Jirka, S.; Klassen, I.; Krumm, J.; Malewski, C.; Rohr, H.; Pakzad, K.	2019	Sustainable management of reservoirs - defining minimum data needs and model complexity	Conference: GRoW- Water as a Global Resource, Status Seminar 2019, Frankfurt	Article	WP1
9	Wagner, A.; Hilgert, S.; Kishi T., R.; Drummond, S.; Kiemle, L.; Nickel, J. P.; Sotiri, K.; Fuchs, S.	2019	Flow-proportional large volume composite sampling to assess substance fluxes	Geophysical Research Abstracts Vol. 21, EGU2019-18649, 2019. EGU General Assembly 2019	Presentation	WP1

10	Wagner, A.; Hilgert, S.; Kattenborn, T.; Fuchs, S.	2018	Proximal VIS-NIR Spectrometry to Retrieve Substance Concentrations in Surface Waters Using Partial Least Squares Modelling	New Technologies in Water Sector. Conference Proceedings. 10th Eastern European Young Water Professionals Conference IWA YWP, 7-12 May 2018, Zagreb, Croatia. p. 194-201.	Article	WP1
11	Rauen W, B.; da Silva M, G.; Hilgert, S.; Sotiri, K.; Knapik, H.; Fernandes C, V.; Dziedzic, M.; Scheer, M.; Bleninger, T.	2018	Reservoir siltation assessment: Critical analysis based on a public water supply reservoir, situated in an urban area.	Brazilian Meeting of Sediment Engineering ENES 2018, Vitoria ES, Brazil	Article	WP1
12	Do Prado, L.; Sotiri, K.; Rauen W, B.; Knapik H, G.; Fernandes C, V.	2018	Particle size distribution of reservoir bottom sediment: are we really measuring what we believe to measure?	Brazilian Meeting of Sediment Engineering ENES 2018; Vitoria ES, Brazil	Article	WP1
13	Hilgert, S.; Sotiri, K.; Fuchs, S.	2021	Comparative overview of reservoir siltation assessment techniques depending on the type of sediment	EGU General Assembly 2021	Presentation	WP1
14	Sotiri, K.; Hilgert, S.; Mannich, M.; Bleninger, T.; Fuchs, S.	2021	A combination of measuring approaches for increasing the accuracy in sediment magnitude assessment in the Passaúna Reservoir	Journal of Environmental Management	Article (submitted)	WP1
15	Hilgert, S.; Sotiri, K.; Fuchs, S.	2021	Effects of Cover Management Factor (C-Factor) on Sediment Yield Modeling and Reservoir Lifetime Predictions	Journal of Soils and Sediments	Article (submitted)	WP1
16	Sotiri, K.; Hilgert, S.; Duraes, M.; Armindo, R.; Wolf, N.; Scheer, M.; Kishi, R.; Pakzad, K.; Fuchs, S.	2021	To what extent can a RUSLE based model be trusted? – case study from Passauna catchment	International Soil and Water Conservation Research	Article (in Prep)	WP1
17	Hilgert, S.; Sotiri, K.; Fuchs, S.	2021	Methods to assess reservoirs' siltation: A review of different case studies		Article (in Prep)	WP1
18	Krumm, J., Haag, I.	2019	Multikriterielle Analyse eines Wasserhaushaltsmodells unter Berücksichtigung der Unsicherheit der Datengrundlage	Forum für Hydrologie und Wasserbewirtschaftung Heft 41.19; poster: Tag der Hydrologie 2019 (March 28/29 2019 in Karlsruhe)	Article, Poster	WP2
19	Krumm, J., Haag, I.	2019	Simulation des Wasserhaushalts für die Einzugsgebiete der Trinkwassertalsperren Große Dhünn (NRW) und Passaúna (Paraná, Brasilien)	Internationaler LARSIM-Anwenderworkshop 2019 (March 19/20 2019 in Wiesbaden)	Presentation	WP2
20	Haag, I., Krumm, J., Aigner D., Steinbrich A., Weiler, M.	2021	Simulation von starkregenbedingtem Hochwasser mit dem Wasserhaushaltsmodell LARSIM		Article in preparation; Presentation	WP2

21	Ishikawa, M ., Haag, I., Krumm, J., Teltscher, K., Lorke A.	2021	The effect of stream shading on the inflow characteristics in a downstream reservoir	River research applications; presentation: PPNW online 2020	Article under review; Presentation	WP2, WP5
22	Krumm, J., Haag, I. , Wolf N.	2019	Adaption des Wasserhaushaltsmodells LARSIM zur Anwendung bei veränderter Datenlage und unter subtropischen Bedingungen am Beispiel des Passaúna (Brasilien)	Forum für Hydrologie und Wasserbewirtschaftung Heft 41.19; poster: Tag der Hydrologie 2019 (March 28/29 2019 in Karlsruhe)	Article, Poster	WP2, WP6
23	Gonzalez, W., Klassen, I., Jakobs, A., and Seidel, F.	2020	3D numerical studies on stratification and mixing processes affecting fine sediment transport in the pre-dam of the Dhünnreservoir in Germany	EGU General Assembly 2020, Online, 4–8 May 2020	Poster	WP3
24	Gonzalez, W., Ishikawa, M., Seidel, F. and Bleninger, T.	2021	3D numerical modelling of the hydrodynamics in a tropical reservoir: investigation of the driving processes		Article (in Prep)	WP3
25	Gonzalez, W., Maudody, M., Wosiacki, L., Seidel, F. and Bleninger, T.	2021	Numerical modelling of the sedimentation in a tropical reservoir: water temperature and wind effects		Article (in Prep)	WP3
26	Gonzalez, W., Mees, D. and Seidel, F.	2021	Study on the complexity reduction of the input data for 3D numerical modeling of the hydrodynamics and sediment transport in a tropical reservoir.		Article (in Prep)	WP3
27	Gonzalez, W., Mees, D. and Seidel, F.	2021	Study on the complexity reduction of the input data for 3D numerical modeling of the hydrodynamics and sediment transport in a Brazilian reservoir	EGU General Assembly 2021	Presentation	WP3
28	Lorke, A.; Rigotti, A.; Sales, G.; Ishikawa, M.; Mannich, M.; Bleninger, T.; Golyjeswski, O.; Gonzalez, W.	2021	Comparison of the application of three models of distinct dimensionalities for the stratification and hydrodynamics of Passaúna Reservoir	In preparation	Article (in Prep)	WP3, WP6
29	Ishikawa, M.; Lorke, A.		Relationship between water quality and hydrodynamics		Article (in Prep)	WP3, WP6
30	Kern, J., Schenk, A., & Hinz, S.	2018	Radiometric Calibration of a UAV-Mounted Hyperspectral Snapshot Camera with Focus on Uniform Spectral Sampling	9th Workshop on Hyperspectral Image and Signal Processing: Evolution in Remote	Presentation	WP4
31	Kern, J., & Schenk, A.	2019	A multi-modal system for monitoring of water quality - setup and first results from Passaúna reservoir	Anais do XIX Simósio Brasileiro de Sensoriamento Remoto (SBSR), (pp. 3157-3160). INPE	Article	WP4
32	Kern, J., Schenk, A., & Hinz, S.	2018	UAS-based hyper-spectral imaging for estimation of water quality parameters in reservoirs.	EGU General Assembly Conference Abstracts (p. 16583), Vienna	Poster	WP4

33	Centeno, J. A. S., Kerm, J., Mitishita, E. A., & Palma, M. E. J.	2020	PCA Band Selection Method For A Hyperspectral Sensors Onboard an UAV	In 2020 IEEE Latin American GRSS & ISPRS Remote Sensing Conference (LAGIRS) (pp. 328-332). IEEE	Article	WP4
34	Schenk, A.; Maier, P.; Kern, J.; Wagner, A.; Keller, S.; Hinz, S.	2019	Monitoring Water Quality with Hyperspectral Close Range Remote Sensing	VACI 2019 – Vietnam International Water Week, Hanoi Vietnam	Presentation	WP4, WP1
34	Jijon-Palma, M. E., Kern, J., Amisse C., Centeno, J. A. S.	2021	Improving Stacked-Autoencoders with 1D Convolutional-Nets for Hyperspectral Image land-cover Classification	Journal of Applied Remote Sensing	submitted	WP4
36	Ishikawa, M.; Bleninger, T.; Lorke, A.	2021	Hydrodynamics and mixing mechanisms of a small subtropical reservoir	Inland Waters, PPNW 2019	Article under review, PPNW 2019	WP6
37	Oliveira, J.; Wosiacki, L.; Gurski, L.; Do Prado, L.; Knapik, H.; Rauen W, B.; Hilgert, S.; Fernandes, C.; Bleninger, T.	2019	Concentration of solids in a supply reservoir: from the field to the laboratory and the manager	Presented at XXIII Simpósio brasileiro de recursos hídricos (2019)	Presentation	WP6
38	Barreto, N.; Gurski, L.; Almeida, E.; Souza, C.; Dec, L.; Do Prado, L.; Hilgert, S.; Kishi, R.; Souza, D.; Knapik, H.	2019	Spatial and temporal variability of trophy degree in Passaúna reservoir - PR	Presented at XXIII Simpósio brasileiro de recursos hídricos (2019)	Presentation	WP6
39	Bernardini, G.; Gurski, L.; Knapik, H.; Fernandes, C.; Bleninger, T.	2019	Use of in situ optical sensors and spectroscopy techniques to study the variation of organic matter dissolved in reservoirs	Presented at XXIII Simpósio brasileiro de recursos hídricos (2019)	Presentation	WP6
40	Maurin, R.; Gräler, B.; Jürrens, E.-H.; Jirka, S.	2019	Managing Earth Observation datasets as multidimensional arrays using SciDB and open standards	Poster at the EGU General Assembly, Vienna, Austria, 7th April 2019	poster presented	WP7
41	Nüst, D.; Jürrens, E-H.; Gräler, B.; Jirka, S.	2020	Accessing environmental time series data in R from Sensor Observation Services with ease	Presentation at the EGU General Assembly 2020, Online, 5. Mai 2020	Presentation	WP7
42	Malewski, C.	2020	Integration of Raster Time Series with the Sensor Web	Presentation at the Geospatial Sensing Virtual 2020, Online, 31. August 2020	Presentation	WP7
43	Malewski, C.	2019	Samplings and Monitoring Programs - Synchronizing Well-defined CSV Files with the New Sensor Web Data Model	Oral gehalten auf der Geospatial Sensing 2019, Online, 3. September 2019.	Presentation	WP7
44	Malewski, C.; Gräler, B.; Förster, C.; Jirka, S.	2019	Kann die Wasserqualität in Stauseen aus Satellitendaten abgeleitet werden?	WasserWirtschaft 109, Nr. 7–8 (1st August 2019): 44–47.	Article	WP7
45	Jirka, S.; Rieke, M.; Remke, A.; Gräler, B.; de Wall, A.	2019	Integration von In-Situ- und (Copernicus) Remote-Sensing-Daten in Informationsinfrastrukturen zur Umweltbeobachtung	26. Workshop Arbeitskreis Umweltinformationssysteme - UIS 2019. Münster, Germany, 2019	Presentation	WP7

46	Gräler, B.; Jürrens, E.-H.; Appel, M.; Malewski, C.	2020	Seamless Integration of Pixel Time Series in the Sensor Web	Geospatial Sensing Virtual 2020, Online, 31. August 2020	Presentation	WP7
47	Gräler, B.; Stasch, C.; Jirka, S.; Malewski, C.; Förster, C.; Remke, A.	2018	Combining remote sensing and in-situ data for water body monitoring	EGU General Assembly 2018, Vienna, Austria, 10. April 2018.	Presentation	WP7
48	Gräler, B.; Malewski, C.; Förster, C.; Jirka, S.	2019	Integration zeitlich hochauflösender Fernerkundungsdaten in das Sensor Web	2. Bochumer Hydrometrie-Kolloquium, Bochum, Germany, 20th February 2019	Presentation	WP7