The Water-Energy-Food Security Nexus in the Kenyan-Ugandan border region

Impact of surface water quality on drinking water supply in the Sio-Malaba-Malakisi River Basin

Master's thesis within the programme
M.Sc. Environmental Engineering
at the Department of Civil, Geo and Environmental Engineering at
Technical University of Munich.

Supervisors TUM	Dr.-Ing. Uwe Hübner, M.Sc. Emil Bein Chair of Urban Water Systems Engineering
Supervisors CapNex	Dr. nat. techn. Mathew Herrnegger Institute for Hydrology and Water Management (HyWa), University of Natural Resources and Life Sciences, Vienna Dr. techn. Jakob Lederer Institute for Water Quality, Resource and Waste Management (IWR), Technical University of Vienna, Vienna
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Submitted	**Munich, 16.05.2021**

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Abstract

The impact of raw water quality on water treatment effort plays an important role for drinking water providers worldwide. At surface water treatment plants, impaired stream water quality caused by sediments, particles, nutrients, and other substances leads to increased treatment effort in the form of chemical use and energy consumption. This may pose challenges to service providers, and potentially to consumers in case additional expenditures are reflected in increasing water prices. While the mentioned relationship has been studied empirically in many high- and middle-income economies using a wide range of methods, no study was yet performed on the African continent. To address this gap, the present study examines water provision in a case study river basin in East Africa that is characterised by extensive agricultural land use and lack of erosion prevention measures. Plant records from three surface water treatment plants, located in the same watershed and operated by the same public utility company, were examined for the mentioned relationship. After identification of the input key input factors to the facilities, time series data on precipitation, raw water quality (represented by apparent colour, turbidity), and treatment effort (represented by coagulant and disinfection chemical uses, backwash water volumes, energy consumption) were compared. Based on the data series, a multiple regression model was developed to estimate the response in chemical treatment effort to varying raw water quality and other environmental factors. The findings show that surface water quality deteriorates over distance from the streams' headwater areas to their respective outlets and indicate a significant correlation between raw water turbidity and coagulant chemical use. For the case study treatment plants, the water-quality elasticity is determined to 0.39, implying that an average decrease in intake water turbidity of 1 % would reduce coagulant use by 0.39 %. Hence, average turbidity reductions of 0.28 NTU (Lirima), 0.30 NTU (Sono), and 4.88 NTU (Malaba-Tororo) would lead to annual savings of 27 kg alum (Lirima), 87 kg alum (Sono), and 252 kg aluminium chlorohydrate (Malaba-Tororo). The results show that reduced stream water turbidity, e.g., through enhanced soil and water conservation measures in the river basin, would decrease water treatment efforts if coagulant dosing at the treatment plants would be adjusted accordingly. The effect on backwash water volumes and hence energy consumption was not included in the analysis.

Keywords

Chemical dosing · Coagulation-flocculation · Drinking water treatment · Sio-Malaba-Malakisi river basin · Stream water quality · Turbidity · Water quality elasticity

Zusammenfassung

Der Zusammenhang zwischen Rohwasserqualität und Aufbereitungsaufwand spielt eine wichtige Rolle für Trinkwasserversorger weltweit. In Anlagen, die Oberflächenwasser zur Aufbereitung nutzen, führen Sedimente, Partikel, Nährstoffe und andere Verschmutzungen zu einem erhöhten Aufbereitungsaufwand in Form von Chemikalieneinsatz und Energieverbrauch. Dies stellt eine Herausforderung für Wasserversorger sowie letztlich für Wassernutzer*innen dar, falls sich zusätzliche Ausgaben in steigenden Wasserpreisen niederschlagen. Während der geschilderte Zusammenhang anhand von Fallbeispielen aus Staaten mit hohem und mittlerem Einkommen unter unterschiedlichsten methodischen Ansätzen empirisch untersucht wurde, liegt bislang keine Studie aus Afrika vor. Um auf diese Wissenslücke zu reagieren, untersucht die vorliegende Arbeit die Wasserversorgung in einem Flusseinzugsgebiet in Ostafrika, das durch intensive Landwirtschaft und eingeschränkte Erosionsschutzmaßnahmen geprägt ist. Datenreihen aus drei Oberflächenwasseraufbereitungsanlagen, die im selben Wassereinzugsgebiet liegen und von demselben Versorgungsunternehmen betrieben werden, wurden bezüglich des geschilderten Zusammenhangs untersucht. Nach der Identifizierung der wesentlichen Stoffeinträge in die Anlagen wurden Zeitreihen in Bezug auf Niederschlag, Rohwasserqualität (dargestellt anhand von Färbung, Trübung) und Aufbereitungsaufwand (dargestellt anhand von Koagulations- und Desinfektionsmitteleinsatz, Rückspülwassermengen, Energieverbrauch) verglichen. Basierend auf den Datenreihen wurde ein multiples Regressionsmodell entwickelt, um die Reaktion des chemikalienbezogenen Aufbereitungsaufwands auf variierende Rohwasserqualitäten und andere Umweltfaktoren abzuschätzen. Die Ergebnisse zeigen, dass sich die Flusswasserqualität mit der Länge des Flusslaufes verschlechtert und dass eine Korrelation zwischen Flusswassertrübung und dem Einsatz von Koagulationsmitteln besteht. Für die drei Fallbeispiele wurde eine Elastizität der Wasserqualität von 0,39 ermittelt, was bedeutet, dass eine durchschnittliche Verringerung der Flusswassertrübung um 1 % den Einsatz von Koagulationsmitteln um 0,39 % reduzieren würde. Hieraus resultiert, dass durchschnittliche Reduzierungen der Flusswassertrübung von 0,28 NTU (Lirima), 0,30 NTU (Sono) und 4,88 NTU (Malaba-Tororo) zu jährlichen Einsparungen von 27 kg (Lirima) und 87 kg Aluminiumsulfat (Sono) sowie 252 kg Aluminiumhydroxychlorid (Malaba-Tororo) führen würden. Die Ergebnisse zeigen, dass eine verbesserte Flusswasserqualität, z.B. durch verstärkte Boden- und Wasserschutzmaßnahmen im Einzugsgebiet, den Aufwand für die Wasseraufbereitung verringern würde, wenn die Chemikaliendosierung in den Wasserwerken entsprechend angepasst würde. Auswirkung auf die Rückspülwassermengen und somit den Energieverbrauch konnten in der Analyse nicht berücksichtigt werden.

Preface and acknowledgements

The present Master's thesis was prepared within the framework of the academic partnership project "Capacity building on the water-energy-food security Nexus through research and training in Kenya and Uganda" (CapNex). CapNex was financed by the Austrian Partnership Programme in Higher Education and Research for Development (APPEAR). APPEAR is a programme of the Austrian Development Cooperation. CapNex focused on capacity building through research, training, and dialogue in the study area since 2016 and was completed in August 2020. I would like to sincerely thank the CapNex coordinators, Dr. Mathew Herrnegger and Dr. Jakob Lederer, for the opportunity to join the project, for their continuous support, and for extensive supervision of this thesis. Furthermore, I would like to thank PhD candidate Paul Omonge for sharing his broad knowledge on the study area with me.

The Ugandan public utility company National Water & Sewerage Corporation (NWSC) was the main partner for this research and provided technical advice, detailed information, and the datasets this study is built on. I would like to thank NWSC and particularly Dr. Irene Nansubuga, Dr. Mohammed Babu, Christopher Kanyesigye, John Ogire, Moses Butele, Fred Businge, Tito Amuku, Sarah Mbabazi and Arima Zubair Isa for their support, their detailed advice and their generous provision of the data presented in this report.

Furthermore, I would like to thank the Friedrich-Ebert-Stiftung Academic Foundation for funding a research stay in the study area in January and February 2020, which allowed to conduct field trips, site visits, expert interviews, and to collect the data required for this research. Particularly, I want to express my gratitude to my supervisor Elena Espinosa for her continuous trust in my plans and endeavours.

Lastly, I would like to express my special thanks to Jesse Nathan Kalange for helping with all necessary arrangements and for making my stay in the study area successful. Without him and Elias Okemer, who took over photography and documentation, this research would not have been possible.

The opinions expressed in this thesis are those of the author and do not reflect the views of NWSC.

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List of abbreviations

ACH	Aluminium Chlorohydrate
Alum	Aluminium Sulphate
CMP	Catchment Management Plan
DWTP(s)	Drinking Water Treatment Plant(s)
dv	Dummy variable
HTH	High Test Hypochlorite
m MSL	Meters above mean sea level
MWE	Ministry of Water and Environment (Uganda)
NOM	Natural Organic Matter
NTU	Nephelometric Turbidity Unit
NWSC	National Water & Sewerage Corporation
OLS	Ordinary Least Squares
PtCo	Platinum-Cobalt Scale
R^2	Coefficient of determination
SD	Standard Deviation
SE	Standard Error
SMMRB	Sio-Malaba-Malakisi River Basin
TSS	Total Suspended Solids
UGX	Ugandan Shilling
VIF(s)	Variance Inflation Factor(s)
WEF	Water-Energy-Food Security

1. Introduction

1.1. Rationale

Many surface water bodies worldwide experience a decline in water quality due to inflows of substances such as sediments, pathogens, salts, nutrients, fertilisers, pesticides, heavy metals, organic wastes, or emerging pollutants (Lintern et al. 2018, 1; Schwarzenbach et al. 2010; UNESCO and UN-Water 2020, p. 20). In the recently published World Water Development Report 2021, the United Nations (2021, p. 13) report that water quality in nearly all major rivers in Africa, Asia, and Latin America has deteriorated. Makarigakis and Jimenez-Cisneros (2019, p. 6) state that half of the world's rivers and lakes are polluted, and identify agriculture as a major contributor to the contamination of groundwater and surface water bodies. Zandaryaa and Mateo-Sagasta (2018, pp. 125–126) confirm this and associate crop production with the release of nutrients, pesticides, salts, and sediments into the environment, and livestock with the release of organic matter, pathogens, and emerging pollutants (e.g., hormones, antibiotics). Besides being non-point sources for the mentioned constituents, farming management practices like tillage and agricultural chemical application can influence water quality by affecting the amount of sediments and particles that are mobilised and delivered into nearby water bodies (e.g., Fawcett et al. 1994). Lintern et al. (2018, p. 9) mention practices like the preparation of land for cropping, creation of gullies, and erosion due to livestock presence as major agricultural impacts. Thereby, agricultural land use and farming practices can adversely affect surface water quality and downstream water uses (Forster and Murray 2007, p. 115).

In areas where lake, reservoir, or stream water is used as a source for drinking water supply, impaired surface water quality has direct impacts on the operation of drinking water treatment plants (DWTPs) and hence water supply. The presence of sediments, particles, and other suspended constituents in the raw water is linked to increasing treatment efforts in the corresponding purification processes, especially in the treatment stages of coagulation, flocculation, sedimentation, and filtration. Several studies indicated that the requirement for treatment chemicals such as alum, polymers, and chlorine varies more than any other factor with raw water quality, and makes up a large portion of the total variable costs for water treatment (e.g., Forster and Murray 2007, p. 117; Westling et al. 2020, p. 4). Furthermore, sediments and particles lead to the requirement of more frequent backwashing of filtration systems, which in turn is associated with increasing electricity consumption at DWTPs (Kraus Elsin et al. 2010, p. 480). Since the price of water reflects the costs for pumping, treating, and distribution of water, additional treatment effort may result in higher water tariffs for consumers (Plappally and Lienhard V 2013, p. 17). Due to the relationships described, source water protection is directly linked to water treatment effort and can hence result in avoided treatment expenditures (Price et al. 2018; Pyke et al. 2002).

The described relationships pose major challenges in the East African countries Kenya and Uganda as well. In Uganda, allegedly high costs of public water supply have received general media attention (Ndyabahika 2019). As Danilenko (2020) reported, the situation was further aggravated due to the recent outbreak of COVID-19. The Ugandan Ministry of Water and Environment (MWE) summarised the issues in their Framework for Water Source Protection (Vol. 1) as follows:

> *"In Uganda, there are extensive forested areas and wetlands, which act as stores of water and perform water purification functions, however increasing population density and demand for land for agriculture, settlement and industrial establishments has led to their widespread clearance. The resulting farm bush landscape is poor at retaining and purifying water and this leads to […] rapid water runoff, soil erosion and water shortages. […] The conventional approach to ensuring high quality water in public water supply systems is the construction and use of water treatment facilities at the point of abstraction. While this is generally effective, there is a capital and on-going cost associated with these systems therefore it is in the interests of the water utility (and end water user) that the quality of water being pumped from the environment is the best possible. The dirtier the water is, the more intensive (and expensive) it is to treat to an acceptable potable quality."*[1]
> (Republic of Uganda 2013, pp. 7–8)

The framework further identified soil erosion due to unsuitable farming practices and deforestation as a widespread problem. Protecting water catchment areas is hence described as "crucial" to retain water and ensure sufficient water supply throughout the year (Republic of Uganda 2013, pp. 7–8). Similar challenges with regards to agricultural land use, water management, and the pollution of surface water bodies are reported from Kenya (e.g., Marshall 2011; Ongwenyi et al. 1993).

A catchment area in which the depicted relationships can be observed to a high degree is the transboundary Sio-Malaba-Malakisi River Basin (SMMRB) in the border region of Uganda and Kenya. The river basin is subject to intensive agricultural land use,

[1] Quoted as in the original publication, not edited by the author.

encroachment of fragile ecosystems, and high yearly precipitation with distinct seasonal variations (NBI 2013). Natural and anthropogenic factors, including steep slopes, heavy rainfalls, flooding, deforestation, and intensive use of land and water for farming with little or no erosion prevention measures result in substantial soil erosion (Roussel 2012, 34–36, 53). This implies that sediments and particles, which might include pathogens and carry nutrients and agricultural chemicals attached to them, are mobilised, and transported to a large extent with wind or surface flow into the streams in the river basin. There, the constituents cause particle-related water quality parameters such as apparent colour and turbidity to increased, which means a deterioration of the water quality.

As public drinking water supply in the SMMRB is predominantly based on surface water, the presence of sediments and particles in streams has a direct impact on water purification. In accordance with the relationships described above, the water constituents are taken up at the intake points of public DWTPs and treated in the respective water purification processes. Since conventional surface water treatment systems are predominant within the SMMRB, increased sediment and particle contents particularly affect the treatment stages coagulation, flocculation, sedimentation, and filtration. The challenges to water treatment are assumed to be increasingly observed in water supply schemes located downstream within the study area. The corresponding variable input factors are, besides treatment time, coagulant chemical use, and backwash water volume, which is associated with energy consumption. Thereby, deteriorated raw water quality, represented by increasing raw water apparent colour and turbidity, leads to an increase in treatment effort represented by the input factors mentioned before. Furthermore, disinfectant chemical use is a variable input factor at a conventional DWTP. As the disinfection stage is located after filtration, it is though not affected by raw water turbidity.

1.2. Research objectives and research questions

The described relationships regarding the impact of surface water quality on drinking water supply in the SMMRB are investigated in the present thesis. In this context, topics related to the Water-Energy-Food Security (WEF) Nexus concept proposed by Hoff (2011) are discussed, including water quality, water supply, agricultural activities, land degradation, erosion, and energy consumption, as well as their interlinkages. The latest scientific discussion on the WEF Nexus was summarised in a review article by Purwanto et al. (2021). The findings of the thesis may be interpreted as incentives for improved land and water management in the upstream catchments of DWTPs, including source water protection to prevent erosion and inflow of sediments and particles into streams.

Thereby, the situation for downstream users such as public water supply, as well as the environment in general, can be improved.

The present study analyses and compares upstream precipitation, intake water quality, and corresponding treatment effort at three case study DWTPs in the SMMRB. To address these relationships, only parameters that describe the presence of sediments and particles in stream water (i.e., apparent colour and turbidity), as well as their corresponding removal processes (i.e., coagulant chemical use) are evaluated. Furthermore, operating parameters of general relevance are considered with regards to processed water volumes (i.e., raw water pumped, service water, final water produced), disinfectant chemical use, and energy consumption. The selected case study DWTPs are Lirima Gravity Supply Scheme, Sono Gravity Supply Scheme, and Malaba-Tororo Water Supply. The schemes are all located on the Ugandan side of the river basin along river Lwakhakha/Malaba (see Figure 8). They use stream water as raw water and are operated by the National Water and Sewerage Corporation (NWSC). NWSC is the public utility responsible for water supply in Uganda. The selection of water supply schemes intends to increase comparability between the DWTPs, while their varying locations within the river basin and hence different relevant upstream areas are particularly interesting for the research questions stated below. Lirima Gravity Supply Scheme is located close to a national park and has thus little to no anthropogenic land and water uses upstream; Sono Gravity Supply Scheme is located about 5 km downstream; and Malaba-Tororo Water Supply is about 40 km further downstream, treating stream water that is clearly influenced by anthropogenic land and water uses.

The main research objectives of the present thesis are to demonstrate the interconnection between surface water quality, represented by the parameter turbidity, and chemical water treatment effort in the SMMRB, and to estimate the extent to which small changes in surface water quality impact water treatment efforts in the river basin. To facilitate this, the following research questions are investigated:

I. Which of the considered raw water quality and operating parameters show characteristic differences in magnitude in

   a. the dry and rainy season, and

   b. between DWTPs located more upstream and more downstream along the streams in the river basin?

II. To what extent are precipitation, raw water quality, and treatment effort correlated at the case study DWTPs?

III. How can the impact of precipitation and raw water quality on treatment effort be modelled for the case study DWTPs using multiple regression and considering the available data?

IV. What are the turbidity elasticities for the selected water supply schemes for the observation period, i.e., the percentage change in treatment effort resulting from a 1 % change in source water quality (after Price and Heberling 2018, p. 199)?

The data for the present thesis was mainly provided by NWSC, the main partner of this research. The provision of internal data by the water supplier allows to derive direct statements about the interconnections between surface water quality and treatment efforts in the selected water supply schemes. NWSC provided detailed plant recordings for both raw water quality and operating parameters, as well as aggregated digital data from their quarterly reporting. Based on a priori knowledge, the parameters mentioned above were selected from the database for further consideration. Only variable input factors were included to represent treatment effort in the analysis, as investments towards the fixed costs are not primarily necessitated by varying or deteriorating intake water quality (Singh and Mishra 2014, p. 78). Due to the availability of data, the observation period was set to extend from September 2016 to January 2020.

1.3. Expected findings and research hypothesis

With regards to the seasonality, pronounced variations are expected for the stream water quality parameters related to the presence of sediments and particles (i.e., apparent colour and turbidity), as well as for the variable operating parameters associated with their removal (i.e., coagulant chemical use, backwash water volume, and energy consumption). For both categories of parameters, higher average values during the wet season and lower during the dry season are expected. This is anticipated intuitively since higher precipitations sums and frequencies detach a bigger amount of constituents in the river basin more frequently, including rainfall-induced erosion processes. Furthermore, the detached materials have increasing opportunities to be transported with the surface runoff and delivered into water bodies during the wet season.

With regards to stream water quality at the intake points of the case study DWTPs, it is expected to find a deteriorating trend over distance from the streams' sources to their respective outlets. This is expected since intuitively, greater relevant upstream catchment areas provide more opportunities for constituents to be mobilised and transported into nearby surface water bodies. Furthermore, large parts of the SMMRB outside of Mount Elgon national park are dominated by agricultural land use with little or no erosion prevention measures, which increases the potential for erosion and mobilisation of constituents. For the DWTPs of Lirima and Sono located upstream within the SMMRB, good to medium raw water quality is expected since both are located comparatively close to the national park and their rather small relevant upstream catchment areas are therefore less affected by anthropogenic land use. For the DWTP of Malaba-Tororo, impaired raw water quality is expected due to a comparatively large relevant upstream catchment area including widespread agricultural activities as well as point source contamination.

For any parameter not directly related to sediments and particles in stream water or to their removal, no variations with the seasonality or location of the DWTP are expected. This includes any water volume, as well as disinfectant chemical dose rate. These parameters are expected to vary mainly with the treatment capacity of the respective plant.

Besides these observations for individual parameters, it is expected to find a significant correlation between intake water quality and water treatment efforts at the case study DWTPs. This will be most pronounced for the sediment related parameter turbidity, and its corresponding water treatment parameter coagulant chemical use. Furthermore, the correlation of precipitation to stream water turbidity is expected to be high. Hence, also a correlation of precipitation to coagulant chemical use will be visible, albeit it is expected to be less pronounced. Parameters related to the disinfection stage are not expected to correlate with any of the parameters mentioned before.

The turbidity elasticities are expected to be positive and similar between the three case study DWTPs. As better raw water qualities (i.e., lower turbidity values) are expected for the upstream DWTPs compared to the downstream DWTP, similar water-quality elasticities would imply smaller treatment efforts at the upstream facilities compared to the one located downstream. The elasticities are expected to be close to the mean turbidity elasticity of 0.14 calculated by Price and Heberling (2018), or at least within the value range of -0.11 to 0.30 identified by the literature so far.

To sum up, the research hypothesis of the present Master's thesis is that surface water quality, represented by the parameter turbidity, has a significant impact on the chemical treatment effort to obtain drinking water quality at the case study DWTPs. Due to the location of the DTWPs and the landscape conditions in the SMMRB, it is expected that both raw water turbidity and treatment effort increase from Lirima via Sono to Malaba-Tororo.

1.4. Structure of the thesis

After this introductory section, Chapter 2 introduces relevant basic concepts as well as the current state of scientific research in a review of selected literature. Here, the study area is introduced, determinants of surface water quality as well as relevant parameters are discussed, the conventional approach for surface water treatment is presented, and empirical studies on the relationship of raw water quality and treatment effort are reviewed. To summarise the information from the literature review and transfer it to the present research, the conceptual framework applied in this thesis is presented. Subsequently, Chapter 3 describes the data and methods that were utilised for this thesis. It also includes a reflection of data-related uncertainties of the present study. In Chapter 4, the analysis results are presented and contextualised with the findings from the literature. Chapter 5 synthesises the most important results of the present thesis and derives conclusions and recommendations. The research questions established in Chapter 1.2 are answered, and practical implications for land and water management in the SMMRB are derived that are mainly addressed to NWSC. Finally, limitations of the study with regards to the research design and methodology are described, and suggestions for further research are made.

Appendix A contains detailed descriptions of the data used in this thesis as well as on its acquisition. Furthermore, a list of relevant contact persons is included. Appendix B provides comprehensive information on the preparations that were required for the quantitative data utilised in this thesis. Appendix C and D include transcripts of expert interviews with key NWSC staff members. Appendix E entails a photo documentation of site visits to the study area and the case study DWTPs.

2. Literature Review

2.1. Description of the study area

2.1.1. General overview

The Sio-Malaba-Malakisi River Basin (SMMRB) is a transboundary river basin in the southern border region of Kenya and Uganda, demarcated by Mount Elgon in the north and Lake Victoria in the south. The area is largely dominated by agricultural land use and faces challenges such as population growth, land degradation, and soil erosion that culminate in water quality deterioration of surface water bodies. In this chapter, the river basin will be briefly introduced, and the mentioned challenges will be discussed.

Lederer (2018) provided a review of scientific and non-scientific literature on the river basin focusing on water management, energy provision, and food security. A number of reports described the general features of the area, including information on environmental conditions, the resources water, land, energy, and biodiversity, as well as human activities, demography, and socio-economic issues (Azza et al. 2017; Claassen 2013; Kaindi 2013; NBI 2013; Roussel 2012). Moreover, the SMMRB is included in the Mpologoma catchment management plan (CMP) by the Ugandan MWE, which contains a status description of the area and establishes management guidelines (DWRD 2018). Scientific publications for the entire river basin or parts are available with respect to land use, soil properties and erosion, landslides, water quality, and socio-economic issues such as livelihoods, of which a selection will be presented in the following.

One goal of the CapNex project was to add to the body of scientific literature on the SMMRB by conducting "case study research projects in the Kenyan-Ugandan border region on the water household, erosion, soil and water conservation measures, and biomass utilization, thereby establishing a data- and knowledge base for WEF nexus investigation and capacity building" (APPEAR 2020). Several publications, reports, and maps with respect to the SMMRB are available or in preparation (e.g., Chasia et al. 2021a; Chasia et al. 2021b; Lederer 2018; Omonge et al. 2021; Schürz et al. 2020; Stecher et al. 2019; Mwanake et al. 2021). A comprehensive list of publications from the CapNex project is available at APPEAR (2021). The present thesis can be regarded as part of this effort.

While other authors defined the boundaries of the SMMRB more extensively (e.g., Roussel 2012, p. 15), the present thesis applies a narrower definition of its geographical extent in accordance with other publications from the CapNex project. Figure 1 shows the study area and its sub-basins and presents spatial information on elevation levels, erosion risk, land cover, and vegetation. Following the definition shown in the figure, the SMMRB comprises of 3,009 km², including the sub-basins Kami (83 km²), Lwakhakha (575 km²), Malaba (486 km²), Malakisi (463 km²), and Sio (1,402 km²) (Herrnegger 1/31/2020, pp. 5–6). In an administrative perspective, the national border divides the river basin in two parts, covering the sub-counties of Bungoma, Busia, Kakamega, and Siaya on the Kenyan side, and the districts of Bududa, Busia, Kwen, Manafwa, Namisindwa, and Tororo on the Ugandan side (Mwanake et al. 2021, pp. 10–11; Roussel 2012, pp. 12–13). The landscape of the river basin is dominated by Mount Elgon, the fourth highest mountain in East Africa with an elevation of up to 4,321 meters above mean sea level (m MSL), and Lake Victoria, the largest lake in Africa and second largest freshwater body in the world by surface area (DWRD 2018, p. 14; NBI 2013, p. 14; United Nations 2021, p. 108). These geographical features are responsible for pronounced spatial variability of weather patterns, significant elevation differences, and steep slopes in the river basin, resulting in vulnerability to landslides (DWRD 2018, p. 14; Mugagga et al. 2012b). The topographical regions of the SMMRB can be subdivided into mountainous, upland, and lowland landscapes (DWRD 2018, p. 18). In mountainous Manafwa district, slope angles between 36° and 58° can be observed, reducing in southern direction down to 0.13° in low-lying Tororo district (Ministry of Natural Resources 1995, 3.1; Mugagga et al. 2012a, p. 1116).

The study area is home to about 1.67 million people, resulting in a population density of approximately 460 people per km² (Herrnegger 1/31/2020, p. 6). Thereby, the SMMRB has one of the highest population densities among the small river basins in Sub-Saharan Africa (Lederer 2018, p. 2). Biomass serves as the main source of energy for the population (Scheren 1995). High rainfall sums support intensive agricultural activities, which are important for the area's economy (DWRD 2018, p. 19). According to Azza et al. (2017, p. 4), the SMMRB can be subdivided into agricultural land, grassland, fallow land, isolated woodlots, and the forest areas of Mount Elgon in the north and Busitema forest reserve in the south. The authors identified rain-fed subsistence agriculture as the predominant land use type. This was confirmed by Herrnegger (1/31/2020, p. 7), who estimated that about 70 to 80 % of the population are engaged in agriculture, mostly in subsistence farming. Typical crops grown in the lower reaches of the SMMRB include maize, sorghum, soybeans, and Bambara nuts. Further information on land cover and land use are provided in Chapter 2.1.4.

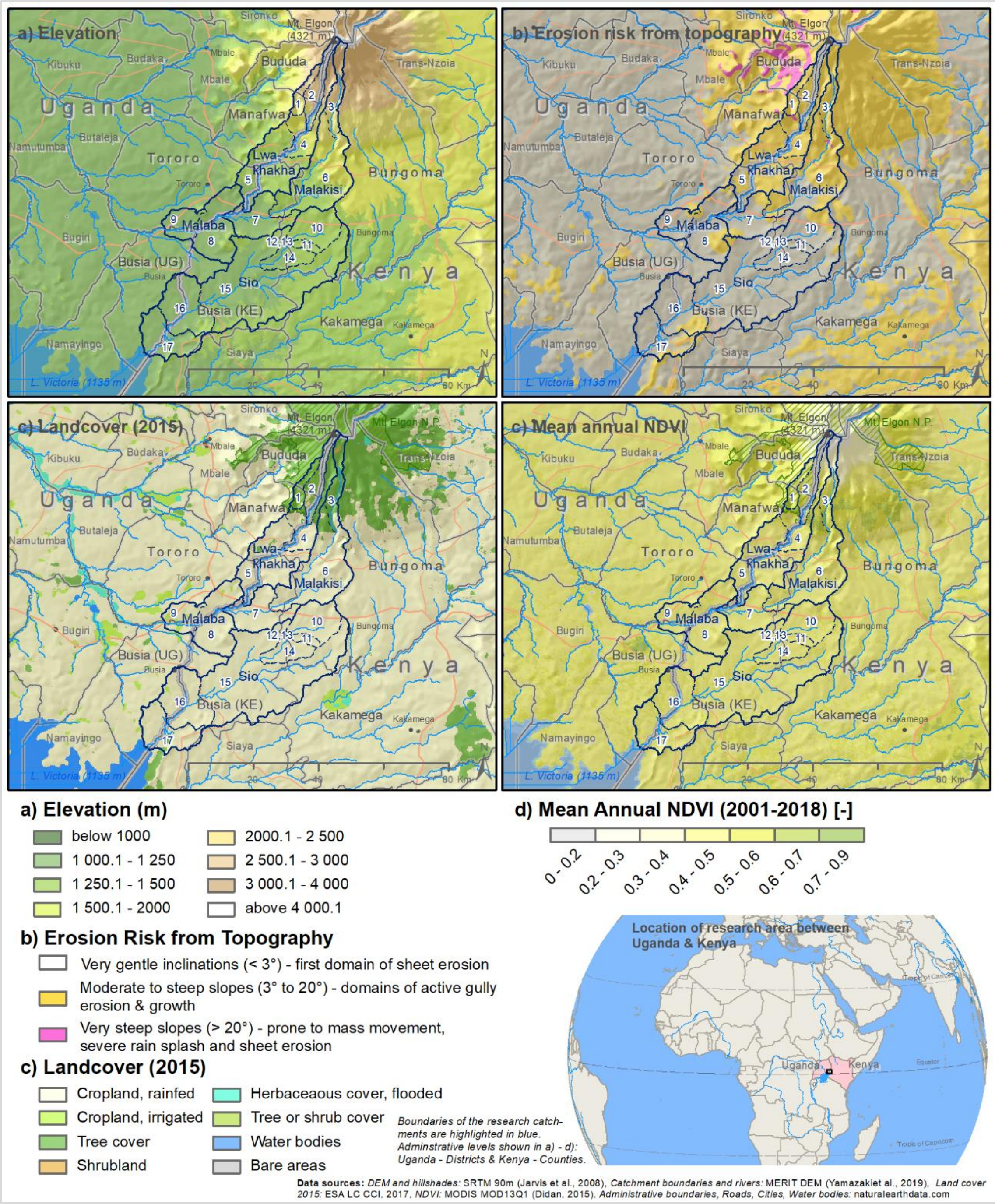

Figure 1: Maps showing selected spatial properties of the SMMRB and its location within Africa. Elevation and topography (a), classification of the soil erosion risk following Ebisemiju (1988) (b), land cover classification with reference year 2015 (ESA LC CCI 2017) (c), and mean annual MODIS NDVI as a proxy for vegetation cover (d). The boundaries of the sub-catchments are shown with blue outlines. Figure from Mwanake et al. (2021, p. 8).

2.1.2. Meteorological conditions

Roussel (2012, p. 16) classified the climate in the SMMRB as humid and sub-humid, modified by the local topography and the presence of Lake Victoria. The author indicated mean maximum temperatures for the SMMRB varying from 27.5 °C in the low-lying areas to about 22.5 °C around the slopes of Mount Elgon. For the latter, the numbers are confirmed by Mugagga et al. (2012b, p. 40) who reported maximum and minimum temperatures of 23 °C and 15 °C for Manafwa and Bududa districts, respectively.

The SMMRB receives a bi-modal rainfall pattern (Mugagga et al. 2012b, p. 40). As Herrmann and Mohr (2011, p. 2505) pointed out, “bi-modal” may either refer to two distinct wet seasons separated by dry seasons, or to a regime with only one wet season involving two distinct rainfall peaks. Considering Herrnegger (2020, p. 3) and Stecher et al. (2019, 10, 19), the latter appears to describe the conditions in the SMMRB better, including one long wet season from March to November with rainfall peaks typically in April/May and October. Consequently, the dry season extends from December to February. This definition for seasonality in the SMMRB will be used consistently throughout this thesis. The approach fits to the observations by Barasa et al. (2011, p. 74), who indicated a short rainy season from March to May, and a longer rainy season from August to November for the Sio sub-catchment.

As stated before, the geographical features of Mount Elgon and Lake Victoria strongly influence precipitation in the SMMRB by increasing total rainfalls and decreasing the severity of the dry period (DWRD 2018, p. 19). Depending on the individual location within the river basin, average annual rainfalls can vary considerably (Mugagga et al. 2012b, p. 40). For example, in the upland and mountainous areas of Mbale, Manafwa, and Bududa districts, excessive rainfalls of more than 2,000 mm/a are common and lead to frequent landslides (DWRD 2018, p. 19; Mugagga et al. 2012b, p. 40). Towards the summit of Mount Elgon, precipitation decreases to 1,750 mm/a, while in parts of Busia sub-county in Kenya, microclimates with only 700 mm/a exist (Ministry of Natural Resources 1995, 3.1; Roussel 2012, p. 16). In recent years, precipitation was reported to become more erratic and unpredictable with regards to amount, duration, and intensity (DWRD 2018, p. 19). According to DWRD (2018, p. 19), this was popularly attributed to the effects of climate change, though the concrete causal relationships need further analysis and verification.

More detailed information on the hydro-meteorological conditions in the SMMRB can be found in a report by Stecher et al. (2019), who synthesised and visualised available datasets regarding precipitation, temperature, and evaporation for the years 1980 to 2017. As the authors were confronted with multiple data gaps and missing precipitation data from the Ugandan side of the river basin, the report illustrated the data limitations that exist with regards to hydro-meteorological data for the SMMRB. To address poor precipitation data availability for the river basin, Omonge et al. (2021) evaluated and compared the reliability of different satellite precipitation products as an alternative source of data for hydrological modelling. The authors found that several products are applicable to replicate rainfall patterns in the SMMRB in time and space, which are however subject to systematic errors, e.g., in high altitude areas and for small rainfall amounts.

2.1.3. Hydrology

From a hydrological perspective, the SMMRB consists of two catchments, namely the Sio and the Malaba-Malakisi catchment (Roussel 2012, p. 8). River Sio originates from hills southwest of Bungoma town in Kenya at an elevation of about 1,450 m MSL, and drains into the Berkeley Bay of Lake Victoria at 1,142 m MSL (Ministry of Natural Resources 1995, 3.1; Roussel 2012, p. 14). In total, the stream is 78 km long, of which large parts form the national border of Kenya and Uganda (Roussel 2012, p. 14). River Malaba originates as river Lwakhakha from the southern edge of Mount Elgon at an altitude of about 4,240 m MSL (Ministry of Natural Resources 1995, 3.1; Roussel 2012, p. 14). After its confluence with river Malakisi about 15 km west of Malaba town, the stream is called river Malaba (Roussel 2012, p. 14). The river flows further in south-western direction and is joined by river Mpologoma, before it drains into Lake Kyoga at about 950 m MSL (Roussel 2012, p. 14). Sio and Malaba are transboundary rivers that have parts of their relevant upstream catchments in both Uganda and Kenya (Ministry of Natural Resources 1995, 3.1), calling for transboundary cooperation of both states and a joint water management (e.g., Grey and Sadoff 2003).

The surface water bodies in the SMMRB are exposed to several water quality and quantity related challenges and threats, which will be discussed in more detail in Chapter 2.1.4. These include erosion induced inflows of sediments, pollution through waste discharges from industry and sewage outflows, over-abstraction of surface water, and adverse changes of the hydrological stream flow regimes due to anthropogenic land use (Roussel 2012, 8, 14). The streams in the SMMRB appear muddy, silty, and turbid, particularly after rainfall events, which indicates elevated colour and turbidity values. These water quality parameters will be defined and described in Chapter 2.2.2.

Tenge et al. (2015) analysed different water quality parameters for river Malakisi, including turbidity, nitrates, phosphates, metal concentrations, conductivity, coliforms, hardness. The authors took samples from four sampling stations in western Kenya, taken within a period of six months during both the dry and wet season. The results indicated an overall mean stream water turbidity of 124 Nephelometric Turbidity Units (NTU), while turbidity values at the individual sampling points ranged from 54 to 238 NTU in the dry season, and from 60 to 289 NTU in the wet season (Tenge et al. 2015, p. 159). The authors attributed elevated turbidity levels to soil erosion that is particularly dominant in the wet seasons (Davies 1996; Tenge et al. 2015, p. 159). Overall, the authors described river Malakisi as polluted and recommend implementing buffer zones along the river system as well as improved management of agricultural practices to prevent soil erosion.

A similar study was published by Ondoo et al. (2019b) for river Sio in Busia County, western Kenya. Stream water from five sampling points was analysed by the authors for the parameters turbidity, temperature, conductivity, pH, dissolved oxygen, and total suspended solids (TSS). Overall, more than half of the evaluated parameters showed significant variations with the seasonal shifts, of which most were higher during the wet season (Ondoo et al. 2019b, p. 1). Turbidity was determined as the highest recorded parameter with clear seasonal variations from 12 to 44 NTU in the dry season and 212 to 482 NTU in the wet season. Furthermore, several parameters such as phosphates and heavy metals showed a high correlation with turbidity, indicating that these substances are transported to the stream together with particles and sediments in surface runoff. Overall, the study describes the water quality of river Sio as poor. Ondoo et al. (2019b, 1, 14) attributed the pollution to domestic and industrial wastewater discharges, as well as inappropriate agricultural practices in upstream areas that lead to soil erosion and hence material transports, particularly during the wet season. According to the authors, this results in threats to terrestrial and aquatic life and increased water treatment costs for downstream users. The study recommends improved land use, proper water treatment and disposal of sewage, as well as replacing agricultural chemical use with organic manure.

2.1.4. Land cover, use, and management

The spatial distributions of land cover and vegetation in the SMMRB are shown in Figure 1 c) and d), respectively. According to Mwanake et al. (2021, p. 9), land use in the river basin is dominated by rain-fed cropland (86 %) and natural forests (11 %), while irrigated cropland (2 %), shrubland (0.4 %) and built-up land (0.16 %) make up only minor parts of the area. Forests are mainly located at the slopes of Mount Elgon in the north and in the Busitema forest reserve in the south of the SMMRB (Azza et al. 2017, p. 4; Mwanake et al. 2021, p. 9).

Several publications identify a continuous conversion of forest cover and other land uses into agricultural areas within the SMMRB that is associated with land degradation, fragmentation, and soil erosion (e.g., Azza et al. 2017; Barasa et al. 2010; DWRD 2018, pp. 18–19; Roussel 2012). Roussel (2012, 8, 35) added the draining of wetlands and encroachment of riverbanks to create land for agricultural cultivation and settlements. Azza et al. (2017, p. 5) confirmed these observations by reporting of conversion of large natural forest areas including riparian zones and seasonal wetlands into agricultural land, leading to land degradation, elevated soil erosion, and sedimentation. Barasa et al. (2010) emphasised widespread loss of soil fertility due to land degradation within the study area. The CMP for the Mpologoma catchment (DWRD 2018, p. 18) identified hot spot areas of land degradation at the slopes of Mt. Elgon in the districts of Bududa, Mbale, and Manafwa, which however lie mostly outside the study catchments. The CMP attributes the land degradation to intensive agricultural land use, poor agricultural practices, deforestation, bush farming, and overgrazing. These issues are referred to as "characteristic" of the upland and mountainous landscapes in the area, leading to negative impacts on food production and food security due to declining soil productivity (DWRD 2018, p. 18). As main driver for the described land use changes, Roussel (2012, p. 8) identified the high population growth in the SMMRB.

Barasa et al. (2011) provided an overview on land use and land cover changes for the Sio sub-catchment for the years 1986 to 2000, which showed that wetlands and bushlands were largely reduced, while small-scale farming increased by 14 % over the time period. Preliminary numbers by Chasia et al. (2021b) pertaining to the entire SMMRB indicated that between 1986 and 2017, cropland area in the SMMRB increased by 52 % and built-up area by 0.78 %, while forest cover decreased by 10 % (numbers from Chasia 2/6/2020, p. 10). Overall, the author states that 68 % of the SMMRB was affected by land use changes in the period 1986 to 2017. Jiang et al. (2014) focused on the Manafwa catchment, an area directly adjacent to the Sio-Malaba-Malakisi river basin. The authors investigated trends in climate conditions and soil erosion for the years 2000, 2006 and 2012. They found a relatively high annual soil loss in the study area, with more than 50 % of the area being exposed to very high erosion risk. Schürz et al. (2020) found similar results for the whole SMMRB, although large uncertainties exist with regards to the soil erosion estimates. In contrast to Barasa et al. (2011), Jiang et al. (2014) could not show any significant trends or patterns for precipitation, risk of soil erosion or land cover change for the Manafwa catchment over the study time. The authors argued that overexploitation of land may be compensated by improved agricultural management.

Regarding the Mount Elgon area, a publication by Mugagga et al. (2012b) is insightful. According to the authors, the Ugandan side of Mount Elgon became a national park in October 1993, with the objective to increase ecosystem conservation in the area. However, the study describes ongoing encroachment into the Mount Elgon national park for cultivation, resulting in almost the entire forest cover below an elevation of 2,000 m being removed. Mugagga et al. (2012b, p. 40) attributed this encroachment to a "strong community desire for more agricultural land" in the Mount Elgon area and identified a major threat to its ecosystem due to the removal of natural vegetation and accompanying land degradation. Furthermore, the authors identified inadequate soil conservation measures for cultivation on the steep slopes, leading to substantial soil erosion in the Mount Elgon area.

The surface water quality issues described in Chapter 2.1.3, including the observations by Tenge et al. (2015) and Ondoo et al. (2019b), were largely attributed to land use in the SMMRB. In fact, Roussel (2012, p. 8) related most challenges for the water resources in the river basin to inappropriate anthropogenic land use and land management. The author mentioned encroachment on river riparian lands and wetlands, farming activities in marginal areas that are vulnerable to soil erosion, and resulting excessive inflow of sediments, nutrients, pesticides, and fertilisers from diffuse sources. For river Sio, Ondoo et al. (2019a, pp. 2–3) reported of extensive anthropogenic activities along the river that lead to pollution. According to the authors, these include agricultural activities such as maize, sugarcane, millet, and sorghum farming, sand harvesting, industrial abstractions for cooling and wash water use, as well as waste discharge into rivers due to poor or missing sewer systems in Busia county (Ondoo et al. 2019a, pp. 2–3; Ondoo et al. 2019b, p. 2). An important factor that was emphasised by several authors is elevated soil erosion caused by steep mountain slopes, intensive agricultural cultivation, and deforestation (Ministry of Natural Resources 1995, 3.1; Roussel 2012, p. 8; Mugagga et al. 2012b, p. 40). In combination with bank and in-stream erosion as well as landslides, high sediment loads are introduced to the surface water bodies of the SMMRB, particularly in the rainy seasons. Roussel (2012, p. 14) reported that sediment inflows and pollution that occur in the upper parts of the Malaba-Malakisi catchment are noticeable along the entire main streams of the catchment, i.e., have far-reaching effects. Furthermore, the author reports of over-abstraction of surface water and waste discharges from industry and sewage outflows in the SMMRB (Roussel 2012, p. 8). Azza et al. (2017, p. 6) observed adverse changes of the hydrological stream flow regimes in the SMMRB and attribute them to land use changes as well, particularly in the Mount Elgon ecosystems.

2.1.5. Drinking water supply

According to the CIA World Factbook (2021a, 2021b), 68 % and 80.8 % of the Kenyan and Ugandan population have access to an improved drinking water source, respectively. While the numbers are higher in urban areas, only 60.4 % and 77.2 % of the rural population have access, respectively. Detailed quantitative information on the water supply situation in the Ugandan part of the SMMRB was provided in the Uganda Water Supply Atlas published by the MWE (Republic of Uganda 2017). According to the Atlas, the shares of people within 1 km (rural) or 0.2 km (urban) of an improved drinking water source were determined to 75 % in Busia district, 69 % in Manafwa district, and 60 % in Tororo district, which are the districts making up the largest share of the SMMRB on the Ugandan side.

Public drinking water supply is organised differently in the two countries. Kenya has a decentralised system with a large number of regional utilities subject to varying operational performances, while Uganda has one national utility associated with less variation in operational performance (van den Berg and Danilenko 2017, 35, 38).

In Kenya, the sector is regulated by the Water Services Regulatory Board (WASREB), a state corporation with the mandate to set, monitor and review standards and enforce regulations to guide the water supply sector in the country (WASREB 2020). The regulations apply to eight water works development agencies that are responsible for water and sanitation infrastructure projects in the country, as well as water service providers subordinate to them. In western Kenya, the responsible water works development agency is the Lake Victoria North Water Works Development Agency (LVNWWDA 2021). Its geographical coverage extends to six counties in western Kenya, among them the counties of Bungoma, Busia, and Kakamega in which the SMMRB is located (LVNWWDA 2021). The agency has appointed four water service providers for direct provision of water and sanitation services in the service area (LVNWWDA 2021). Each of these private limited companies has its own structure and operational performance and operates a varying number of DWTPs to facilitate water supply in the serviced area.

In Uganda, public water supply is provided by the National Water and Sewerage Corporation (NWSC), a public utility company established in 1972 and fully owned by the Government of Uganda (NWSC 2020b). It is one of four key water and environment sector agencies operating under the Ugandan MWE and has the mandate to "provide water and sewerage services in Areas entrusted to it" (NWSC 2018, p. 24). According to van den Berg and Danilenko (2017, 138, 145-146), NWSC is internationally recognised for its successful performance turnaround since 1998, which lead to high access rates in the service areas and financial sustainability. In 2018, the company employed about 3,200 staff members and operated in 256 towns and rural growth centres, divided into 51 operational areas and four regions (NWSC 2020a, 2018, p. 28). In the same year, NWSC achieved nationwide coverage levels for water and sewerage services of 71.6 % and 6.4 %, respectively (NWSC 2018, p. 28). Its customer base is at about 580,000, divided into domestic/household (82 %), institutions/government, commercial (10 %), and public stand posts (2 %) (NWSC 2018, pp. 28–29). In 2018, the annual turnover of the company was at 362 billion UGX (82.3 million €[2]) (NWSC 2018, p. 28). Tariffs for metered water use in the fiscal year 2017-2018 were at 3,305 UGX/m³ (0.75 €/m³) for residential and

[2] To convert Uganda Shillings (UGX) to Euro (€) for the year 2018, a factor of 4400.0025 was used according to Exchange Rates UK 2021.

3,344 UGX/m³ (0.76 €/m³) for institutional or governmental users (NWSC 2018, p. 80). Between 2013 and 2019, NWSC achieved a substantial growth in service coverage from 27 to 253 towns and rural growth centres (NWSC 2019, p. 11). By the end of 2021, NWSC pursues to increase water service coverage to 100 % and sewerage coverage to at least 30 %, by would increase the number of covered towns and rural growth centres to 350 (NWSC 2018, p. 41). The utility operates several DWTPs and piped water supply schemes in the SMMRB, which will be further discussed in Chapter 3.1.

2.2. Surface water quality

2.2.1. General overview

Water quality characteristics vary depending on the source and type of water, as well as on factors such as the hydrogeology of a river basin and human activity in the vicinity of the water body (Crittenden et al. 2012, pp. 13–14). Surface water can be found in natural or artificial freshwater bodies such as lakes, reservoirs, ponds, or streams. In comparison to groundwater, it typically shows higher levels of particulate matter and is more likely to be exposed to anthropogenic chemicals (Crittenden et al. 2012, p. 14). Furthermore, impounded water sources such as groundwater are more stable, while the quality of surface water, particularly of streams, changes more rapidly (Crittenden et al. 2012, p. 198).

Crittenden et al. (2012, 25, 543, 546) stated that natural surface waters contain a variety of organic and inorganic particles. The authors indicated that they are associated with a wide range of particle sizes, numbers, distributions, and shapes. The authors further explained that organic particles include suspended living or dead microorganisms such as viruses, bacteria, algae, cysts, and detritus litter that fell into the surface water. In contrast, inorganic particles such as clay, silt, and mineral oxides usually originate from soils and sediments and typically enter surface waters by erosion processes (Crittenden et al. 2012, 25, 543). To quantify particle contents in water, the parameters true or apparent colour, and turbidity are commonly used, which will be defined in Chapter 2.2.2.

Crittenden et al. (2012, 30, 543) stated that particles in raw water may impact water treatment processes and have health-related implications. According to the authors, removal of particles before any water use is essential for the following three reasons.

- Particles can reduce the clarity of water to unacceptable levels, i.e., cause turbidity and generate colour, which is perceived as unaesthetic.

- Pathogen-related particles such as viruses, bacteria, and protozoa can be infectious agents.
- Particles can offer toxic compounds opportunities for adsorption to their external surfaces. When heavy metals or hydrophobic chemicals (e.g., pesticides) adsorb to them, they may constitute a significant health concern (Post et al. 2012, 2.74).

As Crittenden et al. (2012, p. 546) further elaborated, particles in water remain in suspension for long time periods without aggregating due to their surface charge. However, these suspensions are thermodynamically unstable, and particles will flocculate and settle after sufficient time (Crittenden et al. 2012, p. 546). Since this process is very slow, the authors described it as not economically feasible for water treatment. Treatment technologies such as coagulation and flocculation accelerate this process using treatment chemicals and applying proper mixing, which will be discussed in Chapter 2.3.1.

2.2.2. Parameters to quantify sediments and particles

Crittenden et al. (2012, 25, 30) mentioned gravimetric techniques, electronic particle size counting, and microscopic observations as opportunities to measure particles and suspended solids in water. Corresponding water quality parameters frequently used are colour and turbidity. Both are aggregate characteristics, i.e., the measured values for colour and turbidity are caused by several individual constituents, respectively (Crittenden et al. 2012, p. 25). Regulations for particle concentrations are usually based on turbidity (Crittenden et al. 2012, p. 30).

Crittenden et al. (2012, 18, 41) defined colour as the reduction in clarity of water caused by the absorption of visible light by dissolved substances which include organic compounds (e.g., decaying organic materials, natural organic matter (NOM), or humic and fulvic acids) and inorganic compounds (e.g., natural metallic ions such as iron and manganese). The authors further specified that the colour of a water can be either measured on unfiltered samples, resulting in the parameter apparent colour, or measured on samples after filtration through a 0.45 µm filter, resulting in true colour. Both can be expressed as platinum-cobalt units (PtCo) or light absorption at a specified wavelength (e.g., 254 nm) (Crittenden et al. 2012, p. 463). As turbidity increases the apparent colour of water, the two parameters correlate with one another (Crittenden et al. 2012, p. 41).

Turbidity was defined by Crittenden et al. (2012, p. 19) as the "Reduction in clarity of water caused by the scattering of visible light by particles". According to the authors, it is determined using a light source and a sensor to measure the scattered light and expressed in nephelometric turbidity units (NTU). Post et al. (2012, 2.22) characterise the parameter as a non-specific measure of the amount of particulate matter and suspended solids in water, e.g., of clay, silt, microorganisms, fine organic and inorganic matter, and other substances. The term “non-specific” suggests that turbidity cannot be associated with any quantifiable particle characteristics such as source or type of particles (Crittenden et al. 2012, p. 30).

Particles in water may be pathogenic or offer toxic compounds opportunities for adsorption to their external surfaces. Thereby, the parameter turbidity is in practice associated with infectious diseases (Post et al. 2012, 2.74) and frequently used as an indicator for increased concentrations of bacteria and cysts, amongst others (Crittenden et al. 2012, p. 30). Furthermore, Sulaiman and Hamid (1997) found a close correlation between suspended sediment concentration and turbidity. The authors conclude that turbidity values may be used as a surrogate for suspended sediment concentrations in streams, particularly in small catchments. According to Gianessi and Peskin (1981), sediments can be a transporting vector for chemical contamination, as agricultural fertilisers and pesticides may attach to it. Rügner et al. (2013) found that turbidity can be further used as a proxy for TSS and hydrophobic organic pollutants in stream water. Overall, these interconnections show the importance and significance of turbidity as a water quality parameter.

In stagnant surface waters like lakes or reservoirs, turbidity is usually stable over time and typically ranges between 1 and 20 NTU (Crittenden et al. 2012, p. 30). Warziniack et al. (2017, p. 5) explained this by the fact that such water bodies provide a settling environment which is likely to remove much of the sediments and hence turbidity. In contrast, flowing natural waters such as streams show higher variability. Due to runoff, precipitation, storm events, seasonal impacts, and/or changes in the river flow rate, turbidity values can vary between 10 and more than 4,000 NTU (Crittenden et al. 2012, p. 30). Chang and Liao (2012) indicated turbidities of 5,000 NTU and above. According to Crittenden et al. (2012, p. 30), rapid changes in stream water turbidity of up to several hundred NTU in only a few hours may be observed in some cases, which the authors refer to as “flashing” of streams.

With regards to the water treatment sector, Crittenden et al. (2012, pp. 29–30) described turbidity as an important parameter to control and optimise treatment processes, to assess treatment performance and regulatory compliance, and to compare different water sources or DWTPs with one another. A detailed overview of the importance of turbidity for water treatment utilities was published by Burlingame et al. (1998). The regulatory standard for turbidity in drinking water is at 0.3 NTU, while many DWTPs define individual treatment goals of below 0.1 NTU, which is close to the detection limit of turbidity meters (Crittenden et al. 2012, p. 30). According to Price et al. (2017, p. 4), the parameter is nearly ubiquitously monitored and evaluated by DWTPs worldwide. The authors report that in practice, it is in fact the only water quality parameter monitored at many DWTPs on a regular basis, particularly at plants serving small populations. For DWTPs utilising flowing natural waters as a water source, Crittenden et al. (2012, p. 30) stated that turbidity can be the most variable of the relevant water quality parameters. Particularly for flashing stream water, the authors describe careful turbidity monitoring as “critical” to successfully control the treatment processes at a DWTP.

2.2.3. Influencing factors for stream water quality

A wide range of studies, textbooks, and other publications investigated the impact of environmental factors and landscape characteristics on stream water quality. Besides numerous empirical studies (e.g., Al-Saady and Abdullah 2014; Bahar et al. 2008; Bolstad and Swank 1997; Camara et al. 2020; Cunha et al. 2016; Ding et al. 2015; Kupiec et al. 2021; Ribolzi et al. 2011; Sliva and Dudley Williams 2001), various authors examined the underlying principles that lead to the inflow and presence of certain substances in streams (e.g., Afed Ullah et al. 2018; Allan 2004; Granger et al. 2010; Meybeck et al. 1990; Hurley and Mazumder 2013). The current state of knowledge regarding the underlying principles was provided in a review article by Lintern et al. (2018). The authors synthesised that the influencing factors for stream water quality in river basins can be categorised into land cover, land use, land management, atmospheric deposition, geology and soil type, climate, topography, and catchment hydrology. In line with a conceptual framework established by Granger et al. (2010), the authors assigned these influencing factors to one or more of three key processes, namely sources, mobilisation, and delivery of substances into receiving streams. The respective relationships between influencing factors, processes, and stream water quality are illustrated in Figure 2. Furthermore, Lintern et al. (2018, 10-11) provided an extensive overview of key influencing factors and how they impact sources, mobilisation, and delivery of suspended solids, salts, and nutrients in catchments.

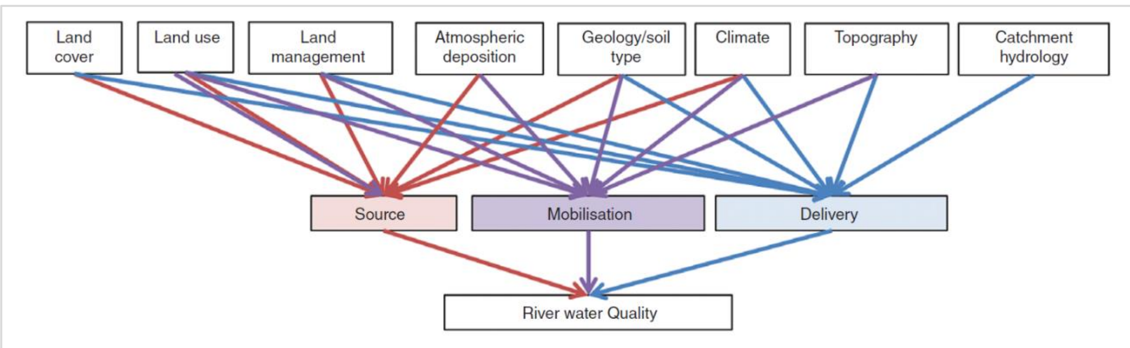

Figure 2: Influencing factors of landscape characteristics on source, mobilisation, and delivery of constituents into streams in any given river basin. Figure taken from Lintern et al. (2018, 5).

Sources

According to Lintern et al. (2018, pp. 2–3), constituents may either be introduced to catchments or streams from external sources (e.g., application of agricultural chemicals by farming activities), or may be already present because of natural processes (e.g., in the soils). The latter includes particles that are formed by biological activity, chemical precipitation, or through atmospheric deposition directly in the water column and hence do not require mobilisation and delivery into a water body (Crittenden et al. 2012, p. 31).

In general, sources of substances can be classified as natural or anthropogenic. According to Crittenden et al. (2012, pp. 31–33), the principal natural sources of particles in catchments or streams are weathering processes and biological activity. Weathering was defined by the authors as the contact of water with minerals, rocks, or soil. Thereby, colloidal particles such as clay, silica, ferric oxide, aluminium oxide, and magnesium dioxide, as well as suspended particles such as silt, sand, clay, and other inorganic soils, are formed (Crittenden et al. 2012, p. 31). Biological activity leads to both the formation of algae, bacteria, and other microorganisms in natural waters, and to the decomposition of organic matter in the environment which may introduce various organic polymers and cell fragments into surface water bodies (Crittenden et al. 2012, pp. 31–32). For anthropogenic sources, Crittenden et al. (2012, pp. 31–32) mentioned industrial, municipal, agricultural, and other human activity. As an example, the authors indicate that industrial activity may lead to direct pollution of surface water with industrial resides and organic pollutants. Also, municipal wastewater treatment plant discharges can be a major point source for organic contaminants in catchments (Crittenden et al. 2012, p. 59). Even after effective treatment, pollutants such as emerging organic compounds may be found in the plant's effluents (Crittenden et al. 2012, p. 59).

A further classification can be made in respect to point and non-point sources (i.e., diffuse sources). Crittenden et al. (2012, p. 56) defined point-source constituents to originate from a specific site (e.g., industrial discharges, waste disposal, wastewater treatment plant effluent), while non-point source constituents enter water bodies over a broad area (e.g., runoff from urban or agricultural areas).

As Figure 2 indicates, land cover, land use, land management, atmospheric deposition, geology and soil type, and climate may constitute or affect constituent sources in a catchment. According to Price and Heberling (2018, p. 196), the causal relationships between land use and surface water quality have been well established. For example, forests are generally considered as favourable for stream water quality. According to Warziniack et al. (2017, p. 4), they remove pollutants from water, stabilise surrounding soils and hence reduce sediment runoff, provide leaves and other litter to protect the soil from precipitation impacts, and limit exposure to contaminants by limiting human activity within a watershed. In contrast, anthropogenic land uses such as urban and agricultural land uses are considered more problematic (e.g., Baker 2003; Price and Heberling 2020). Particularly the impacts of agricultural land use on stream water quality were discussed extensively in the literature (e.g., Kupiec et al. 2021; Mateo-Sagasta et al. 2018). Holmes (1988, p. 356) indicated that agricultural areas are sources for sediments, nutrients, and pesticides that may lead to water quality degradation. This is confirmed by Warziniack et al. (2017, p. 14), who found that agricultural activities eventually increase turbidity in surface water. Brown and Froemke (2012) add land related factors such as the population living in a watershed, kilometres of roads, and grazing density within the watershed to affect downstream surface water quality. An extensive overview of land management strategies for urban and agricultural areas to limit sources and mobilisation of constituents was provided by Lintern et al. (2018, p. 10).

Mobilisation

According to Lintern et al. (2018, p. 3), constituents are either mobilised by low-energy processes (e.g., desorption or mineralisation) or by high-energy processes (e.g., erosion, landslides, or failure). As Figure 2 illustrates, the mobilising processes in a catchment are influenced by land use, land management, atmospheric deposition, geology and soil type, climate, and topography. Inorganic particles such as clay, silt, and mineral oxides are typically introduced to surface water by natural erosion processes (Crittenden et al. 2012, p. 543). According to Lintern et al. (2018), suspended solids can be displaced by wind, water, and anthropogenic activities, or mobilised by weathering. Regarding land use, the authors compiled that sediments may be mobilised by erosion from construction sites, erosion induced by livestock, agricultural preparation of land for cropping, or creation of gullies due to agricultural practices. Furthermore, both rainfall intensity and volume can lead to mobilisation of sediment, nutrients and other particles in a catchment (Lintern et al. 2018, 13).

Delivery

According to Lintern et al. (2018, p. 3), the delivery of constituents into receiving streams occurs either by surface flow, subsurface flow, or artificial drainage systems. As Figure 2 illustrated, land cover, land use, land management, geology and soil type, climate, topography, and catchment hydrology influence delivery processes in a catchment.

When entering the water bodies, constituents such as clay, silt, and mineral oxides are suspended in the water due to turbulence and mixing (Crittenden et al. 2012, p. 31).

A summarising overview of sources, mobilisation, and delivery of sediments into receiving streams in any given river basin is provided in Figure 3.

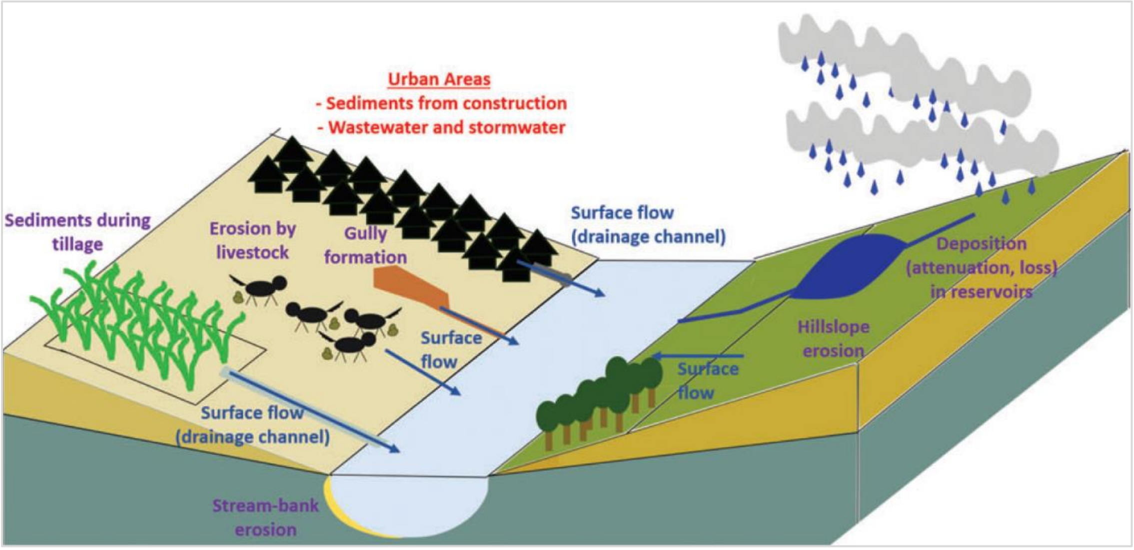

Figure 3: Sources (indicated in red), mobilisation (indicated in purple), and delivery (indicated in blue) of sediments in a given river basin. Figure taken from Lintern et al. (2018, 4).

According to Lintern et al. (2018, 2), anthropogenic impacts regarding changes in land use and land cover were extensively studied and are widely known today (e.g., Allan 2004; Polyakov et al. 2005). In contrast, the authors stressed that the effects of naturally occurring landscape characteristics have been studied to a lower extent. Furthermore, the authors identified a knowledge gap with regards to the interactions and cross correlations between individual landscape characteristics and their effects on stream water quality. Sliva and Dudley Williams (2001) reported of uncertainties regarding whether land use over the entire catchment is a better predictor of surface water quality, or land use in the riparian zones close to the surface water bodies. The authors report of mixed scientific results with respect to this topic.

2.3. Surface water treatment

2.3.1. Conventional water treatment

Basic information on commonly applied technical approaches in surface water treatment and their underlying principles are delineated in several textbooks (Brandt et al. 2017; Crittenden et al. 2012; Davis 2010; Edzwald 2012; Hendricks 2011; Howe et al. 2012; Sincero and Sincero 2003). In the following, a short overview of surface water treatment will be given, with a focus on conventional treatment systems and the removal of sediments and particles. The textbook by Crittenden et al. (2012) was used as main reference, while other publications were considered as well. For further details, please refer to the publications listed above.

Each type of water source requires a different treatment strategy to achieve the desired quality of treated water (Crittenden et al. 2012, 14, 189). For the treatment of surface waters, a number of factors should be considered, including typical quality of the water source, event water quality, i.e., the variability that occurs during specific seasonal events, as well as source stability (Crittenden et al. 2012, p. 198). Colour and turbidity are typically removed from surface water by a combination of coagulation, flocculation, clarification (e.g., sedimentation), and filtration (Post et al. 2012, 2.75). The corresponding treatment approach is called conventional water treatment (Crittenden et al. 2012, p. 204). A schematic flow diagram is shown in Figure 4. According to Crittenden et al. (2012, 193, 204), this treatment approach works well for raw waters with moderate to high turbidity (> 20 NTU), high colour (> 20 CU), and/or high TOC (> 4 mg/L). Conventional treatment plants can effectively remove NOM, taste, odour, and colour, are hydraulically stable, and generally have greater operational flexibility and require less attention during operation compared to other treatment approaches (Crittenden et al. 2012, 193, 204-205). As loading rates are typically low, large surface areas and hence a lot of land are required for conventional treatment plants (Crittenden et al. 2012, p. 205).

Within the treatment train shown in Figure 4, particles and NOM are mainly removed during sedimentation and size exclusion, e.g., filtration (Crittenden et al. 2012, 34, 543). However, Crittenden et al. (2012, 34, 543, 546) stated that these treatment processes alone would not be sufficient to reduce the respective substances to acceptable levels, since many particles and dissolved constituents do not settle in a reasonable time. Therefore, the effective range of the processes is greatly extended by previous conditioning of the water with treatment chemicals, so-called coagulants, that help in removing the particles.

Adequate turbidity removal also leads to a partial removal of pathogens and non-pathogenic bacteria in the water, since both aggregate with particles, with each other, and with the chemical coagulants used during water treatment (Post et al. 2012, 2.22-2.23). Crittenden et al. (2012, p. 211) indicated that removing the turbidity-causing materials in raw water results in the generation of water treatment residuals that consist of organic and inorganic solids, algae, bacteria, colloids, and other substances. According to the authors, these residuals that are largely contained in the treatment sludge need further treatment before reuse and/or disposal, which is part of the residuals management.

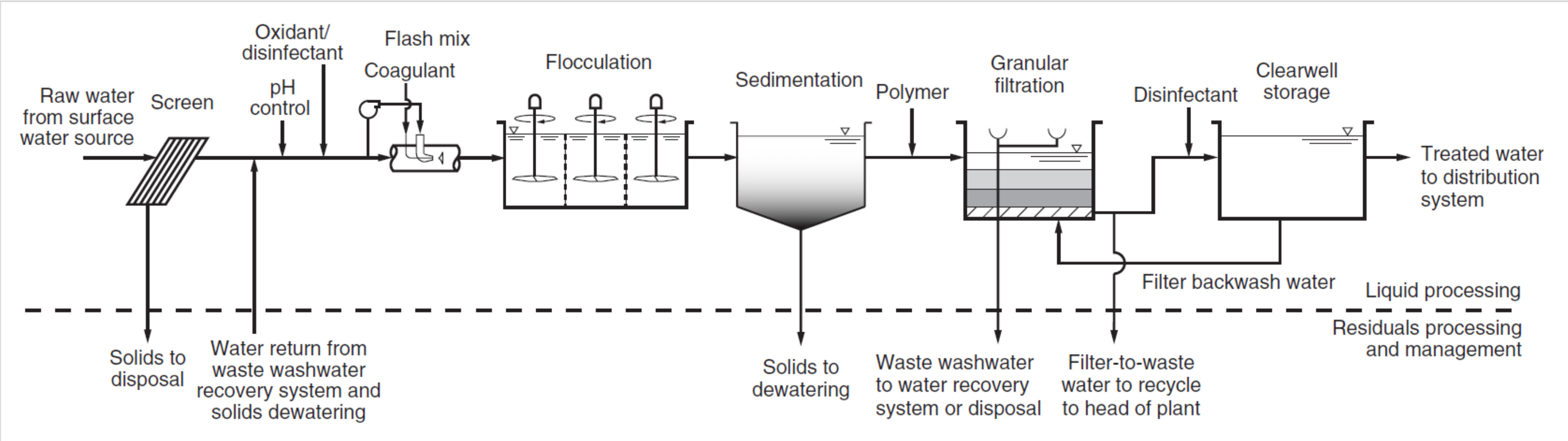

Figure 4: Schematic flow diagram for a conventional water treatment train typical for the purification of surface water. Figure from Crittenden et al. 2012, p. 206.

Coagulation and flocculation

After inflow or pumping, screening, and optional pH control and pre-disinfection, the coagulation/flocculation stage is the first treatment stage at conventional water treatment plants. According to Brandt et al. (2017, p. 336), the processes are essential in the treatment of most surface waters. The authors stated that they help to remove turbidity and colour, as well as a variety of other substances of natural and anthropogenic origin, including cysts and oocysts, biological matter, viruses, and organic substances. Crittenden et al. (2012, p. 565) add the removal of disinfection by-product precursors in the form of NOM. Furthermore, chemical phosphorus removal can be achieved by the formation of precipitates and their entrapment into flocs (Ratnaweera and Fettig 2015, p. 6575). The specific objectives of the coagulation process depend on the raw water source as well as the nature of the suspended, colloidal, and dissolved organic constituents present in the water (Crittenden et al. 2012, pp. 544–545).

Crittenden et al. (2012, 190, 542) defined the process of coagulation as the addition of one or more chemical(s) to water that destabilise particles so that aggregation and particle growth can occur during flocculation. These chemicals, e.g., ferric chloride, alum, or polymers, are called coagulants (Crittenden et al. 2012, p. 190). The individual processes that occur during coagulation include destabilisation of small suspended and colloidal particulate matter; adsorption and/or reaction of colloidal and dissolved NOM to particles; and creation of flocs consisting of suspended, colloidal, and dissolved materials that sweep through the water for subsequent treatment (Crittenden et al. 2012, p. 545). In case NOM is present in the treated water, it reacts with and consumes coagulants, which increases the required dose to achieve effective turbidity removal (Crittenden et al. 2012, p. 54). As coagulant chemical use is a variable input factor in conventional water treatment, further information on types and dosing of coagulant chemicals is provided separately in Chapter 2.3.2.

According to Davis and Edwards (2014, p. 303), influencing factors for coagulation are pH, temperature, source water composition, and coagulant type, among others. For each water quality and type of coagulant, an optimum pH range exists. Brandt et al. (2017, p. 340) stated that the "optimum pH range corresponds to that over which minimum solubility of the hydrolysed coagulant products occurs and maximum turbidity and colour removal is achieved." In most DWTPs, the optimum pH is between 6 and 8 (Crittenden et al. 2012, p. 565). Just like strong acids would, coagulants decrease the pH of the processed water and consume alkalinity (Crittenden et al. 2012, p. 566). In case the natural alkalinity of the raw water is not sufficient to buffer the pH after adding the coagulant(s), it might be required to adjust the pH by adding substances such as caustic soda, lime, or soda ash that add alkalinity and prevent the pH from falling too low (Crittenden et al. 2012, p. 567).

Flocculation was defined by Crittenden et al. (2012, p. 191) as the aggregation of particles that have been chemically destabilised through coagulation. Thereby, larger particles ("flocs") are formed that are easier removed from the water than the original particles (Crittenden et al. 2012, 542, 544). The removal of the aggregated flocs is then performed in subsequent separation processes such as gravity sedimentation and/or filtration (Crittenden et al. 2012, pp. 190–191).

In terms of time required for each process, coagulation and flocculation show clear differences. As Hudson and Wolfner (1967) found, "coagulants hydrolyze and begin to polymerize in a fraction of second after being added to water". As a rule of thumb, coagulation occurs in less than 10 seconds, while flocculation takes between 20 and 45 minutes (Crittenden et al. 2012, p. 544). Therefore, mixing plays a critical role for both processes. Rapid and intense initial mixing, also known as blending, is important to ensure a proper coagulation process (Crittenden et al. 2012, 368, 572–573). During flocculation, the water is brought into motion to generate contact between the particles after the coagulation has neutralised their natural repulsion to each other (Crittenden et al. 2012, p. 363). Thereby, mixing is crucial as the mixing energy contributes to the rate of the flocculation reaction (Crittenden et al. 2012, p. 363).

Sedimentation

Sedimentation is the process of separating settleable solids, i.e., particles greater than 0.5 mm, by gravity (Crittenden et al. 2012, p. 192). In conventional water treatment, it is arranged after coagulation and flocculation and before the water enters the filtration stage.

Filtration

Crittenden et al. (2012, 191, 728) defined granular filtration as follows: "by passing water through a bed of granular material, particles are removed by transport and attachment to the filter media". Plappally and Lienhard V (2013, p. 10) described granular media gravity filters that remove non-settling flocs after coagulation and sedimentation as the "most important and expensive procedure" in conventional water treatment systems.

The filtration stage requires regular backwashing of the filter material. As backwash water volumes may be considered as a variable input factor in conventional water treatment, backwashing will be discussed separately in Chapter 2.3.3.

Disinfection

Disinfection in water treatment was defined by Crittenden et al. (2012, p. 191) as the addition of chlorine, chloramines, chlorine dioxide, ozone, or UV light to the processed water, followed by a specified contact time, with the objective to inactivate pathogens such as viruses, bacteria, and protozoa.

High raw water turbidity levels can reduce the efficiency of disinfection by creating a disinfection demand (Post et al. 2012, 2.23). This is due to the fact that soil erosion from agricultural fields and feedlots may be associated with pathogens and contribute to the need to disinfect water supplies (Holmes 1988, p. 356). According to Sthiannopkao et al. (2007, pp. 710–711), however, this effect only affects pre-chlorination. The authors stated that chlorination after the filtration stage is independent on the amount of water turbidity (MWA 2004, as cited by Sthiannopkao et al. 2007, pp. 710–711).

Multiple barrier approach

According to Crittenden et al. (2012, 165, 167) the idea of the multiple barrier approach is that water providers should not only perform effective water treatment as well as management of the conveyance and distribution system, but also engage in watershed management and source water protection. The authors stated that in combination, these processes and activities may constitute several barriers that limit the presence of contaminants in the final drinking water. Multiple barriers increase the robustness and reliability of a water supply system, and reduce exposure to risks associated with process failures (Crittenden et al. 2012, pp. 218–219).

2.3.2. Types and dosing of coagulant chemicals

Types of coagulant chemicals

The type of coagulant chemical applied in water treatment depends on a number of factors, including the concentration and characteristics of particles and NOM in the water, various water quality parameters, temperature, and the characteristics of the coagulant (Crittenden et al. 2012, p. 561). In general, coagulant chemicals can be categorised into inorganic metal coagulants and polymers (Bratby 2016, p. 33). For the present thesis, metal coagulants are of interest, particularly those based on aluminium. When metal coagulants are added to water, they immediately dissociate and hydrolyse rapidly in a relatively uncontrolled manner to form various hydrated reaction products, namely mono- and polynuclear species of varying charge that interact with the particles in water (Bratby 2016, 39, 46; Crittenden et al. 2012, 543,564). These metal hydrolysis species, of which certain are effective for treatment, are formed depending on the coagulant dose, pH, and efficiency of rapid mixing (Bratby 2016, p. 39). When inorganic metal coagulants are added in excess, chemical precipitates are formed (Crittenden et al. 2012, p. 543).

Most commonly used inorganic coagulants are salts of aluminium and ferric ions such as aluminium sulphate (alum) and ferric chloride, as well as prehydrolysed salts of these metals (Crittenden et al. 2012, 543, 561). Aluminium coagulants enjoy worldwide popularity due to their effectiveness, ready availability, and relatively low costs (Bratby 2016, p. 34). Crittenden et al. (2012, p. 562) provided an overview of common inorganic coagulants including their chemical formula, molecular weight, and application. Alum is usually sold in hydrated form as $Al_2(SO_4)_3 \cdot xH_2O$, of which the specification $Al_2(SO_4)_3 \cdot 14H_2O$ is most widely used worldwide since it is the least expensive coagulant (Crittenden et al. 2012, p. 562). According to Chew et al. (2016, p. 3157), alum has a lower price per unit and is commonly available, while a much higher dose is required and a significant pH drop is induced which frequently requires chemicals for pH adjustment.

While the described inorganic metal coagulants are well suited to treat turbidity and NOM in the water and are therefore used predominantly worldwide, prehydrolysed metal salt coagulants gained popularity over the last few decades (Davis and Edwards 2014, p. 304). These coagulants were developed as a reaction to the unpredictability and uncertainty associated with alum and ferric salts, which are difficult to control due to the formation of various mono- and polynuclear metal species after addition to water (Crittenden et al. 2012, 564, 573). According to Crittenden et al. (2012, 570-571, 573) and Gebbie (2001, pp. 41–42) the advantages of prehydrolysed metal salts include:

- Potentially more effective and hence lower dose requirements for effective coagulation,
- Better characteristics of the formed flocs (tougher and denser),
- Low alkalinity consumption and less sensitive towards the pH compared to unmodified metal coagulants, can be used in a pH range of 4.5 to 9.5,
- Less sensitive towards the initial blending time since the metal salts are prehydrolysed,

- Lower levels of residual aluminium in the treated water, typically about 0.01 to 0.05 mg/L,
- Less sludge production compared to unmodified metal coagulants at equivalent dose.

Aluminium-based prehydrolysed coagulants are polymers with the general formula $Al_a(OH)_bCl_c(SO_4)_d$ (Crittenden et al. 2012, p. 573). Since most formulations do not contain any sulphate, Gebbie (2001, p. 40) indicated the general formula as $(Al_nCl_{(3n-m)}(OH)_m)_x$, where x indicates the polymeric structure of the molecule. Numerous aluminium-based prehydrolysed coagulants are commercially available in liquid form or as dried granular powder that contain between 5 % and 13 % Al in the liquid products, compared to an Al content in alum of approximately 4 % (Bratby 2016, p. 41). Common formulations include Polyaluminum Chloride with the formula $Al_2Cl_3(OH)_3$ (n = 2, m = 3), Aluminium Chlorohydrate (ACH) with the formula $Al_2Cl(OH)_5$ (n = 2, m = 5), and Polyaluminium Chlorohydrate with a formula similar to ACH (Gebbie 2001, p. 40). Though ACH is more hydrated, Polyaluminum Chloride and ACH show only minor performance differences in water treatment (Gebbie 2001, p. 40).

Aluminium Chlorohydrate (ACH) is a high-density prehydrolysed metal coagulant that can be used as a primary coagulant as well as sludge conditioner (Bratby 2016, p. 40). The commercially available product contains approximately 13 % Al, in comparison to alum that contains about 4 % Al (Bratby 2016, p. 40). In general, ACH can improve final water quality, control costs, enhance the efficiency of the coagulation stage, and improve phosphorus removal (Ruehl 1999). Due to its characteristics, ACH is particularly beneficial for the treatment of raw water with variable levels of turbidity, particles, organics, and other parameters that change rapidly (Ruehl 1999). However, Chew et al. (2016, p. 3157) indicated that ACH is more costly and not commonly available. Furthermore, disadvantages exist with regards to the removal of dissolved organic carbon, humic and fulvic colour constituents, and trihalomethane precursors (Gebbie 2001, p. 42).

Dosing of coagulant chemicals

While the coagulation process and its influencing factors and contaminant removal are well understood in qualitative terms (see Chapter 2.3.1), no comprehensive or generally accepted mathematical description of the process was developed up to today that takes all relevant parameters into account and allows for control and optimisation of the process as well as prediction of coagulation efficacy (Crittenden et al. 2012, p. 561; Davis and Edwards 2014, pp. 303–304; Ratnaweera and Fettig 2015, p. 6575). Sophisticated concepts based on digitally measured water quality parameters are emerging, but in practice, process control and optimisation largely rely on data from jar tests and simple flow-proportional dosing concepts (Ratnaweera and Fettig 2015, p. 6574). The procedure of jar testing was described in detail by Teefy et al. (2011). Crittenden et al. (2012, p. 578) described its purpose as simulating, “to the extent possible, the expected or desired conditions in the coagulation–flocculation facilities” and thereby deriving optimal coagulant doses for effective water treatment.

Dearmont et al. (1998, p. 851) stated that “low-turbidity raw water supply requires more coagulant than a more turbid raw water supply. Thus, as turbidity increases, less coagulant is needed. However, once turbidity increases above some point, the needed amount of coagulant rises.” Empirical analyses showed that usually, increasing dosages of coagulant chemicals lead to increasing percentage reductions in turbidity from water (Mukherjee et al. 2012, p. 302). If the optimum alum dose and pH are met, turbidity in the sample water is minimised (Crittenden et al. 2012, p. 579). The optimum coagulant dosage is subject to constant change as raw water quality and hence particle concentration and NOM change (Crittenden et al. 2012, p. 579). Typical alum doses range from 10 to 150 mg/L, depending on raw water quality and particularly turbidity (Crittenden et al. 2012, p. 572). Optimum conditions for particle removal by sweep flocs require an alum dose of 20 to 60 mg/L at pH values between 7 and 8 (Amirtharajah and Mills 1982).

An example study for the treatment of a tropical surface water by coagulation and flocculation with alum was published by Gone Droh et al. (2008). The sample raw water for the study had a turbidity of 15.1 NTU and pH of 6.61. By performing enhanced coagulation jar tests for different alum doses (range 80-125 mg/L) and pH values (range 4-6), the authors determined that for a given pH, the efficiency of turbidity removal increased with increasing alum dose. For the sample water, the authors found an optimum removal of turbidity (98 %) and dissolved organic carbon (70 %) for 100 mg/L alum at pH 5.

Ruehl (1999) reported about empirical observations from a DWTP treating raw water subject to a wide range of turbidity with ACH. When raw water turbidities increased from 55 to 220 NTU, ACH doses were adjusted from 37 mg/L to 45 mg/L. These comparatively small ACH doses resulted in small filtered water turbidities of 0.05 NTU, minor requirements for pH adjustment, and reduced chemical sludge amounts (Bratby 2016, p. 41; Ruehl 1999). Chew et al. (2016, p. 3158) indicated an average ACH dose of 11.0 mg/L for the media filtration system evaluated in their case study. According to NSF International (2021), the ACH types Zetafloc 2300 and Zetafloc 2300L are intended for a maximum concentration of 250 mg/L.

For the direct comparison of ACH and alum, empirical studies indicated an overall advantage of using ACH since it significantly reduced chemical sludge volumes, backwash water volumes, and final water residual aluminium (Jones (1999), as cited in Bratby 2016, pp. 40–41). However, there is also evidence that final water turbidity was lower with alum (Bratby 2016, p. 41). A conference paper by Gebbie (2001, p. 44) included several empirical observations from Australian water treatment plants that used alum and/or ACH as coagulants for the treatment of surface waters. An example described by the author is the treatment of stream water from the Murray River in Australia that showed a turbidity of 20 to 40 NTU under normal stream flow conditions. The Swan Hill Water Treatment Plant applied liquid alum doses between 30 and 60 mg/L for treatment of the stream water to drinking water quality (Gebbie 2001, p. 44). After the process train was modified to the application of ACH, dose rates of 6 to 12 mg/L were sufficient for treatment, i.e., about 20 % of the doses required for alum before (Gebbie 2001, p. 44). Besides this reduction in coagulant dose, the author mentioned that pre- and post-treatment with lime to adjust pH and alkalinity could be discontinued, which was described as another advantage. For an in-filter DWTP using dissolved air flotation in Rainbow, Victoria, the author reported of raw stream water turbidities of only 1.5 to 2.5 NTU, but comparatively high pH and total dissolved solids levels. For this DWTP, the required coagulant dose rates were predicted with the software WaterQual to 90 mg/L for alum and 20 mg/L for ACH, i.e., ACH doses were about 22 % of the doses required alum doses (Gebbie 2001, p. 45). It is worth noting that the described observations are empirical and depend on the individual raw water qualities and treatment trains of the DWTPs.

Figure 5 shows a comparison of empirical observations for the dosing requirements of alum and ACH as a reaction to varying raw water apparent colour and turbidity. As the upper diagram indicates, considerably higher dose rates of alum are necessary to achieve a defined treated water quality compared to the use of ACH, or to a combination of both. Ruehl (1999) stated that ACH usually requires about one third of the dose of liquid alum. This observation was confirmed by Gebbie (2005, p. 77). Wang et al. (2008) indicated that the use of ACH saves 60-70 % dose in comparison to alum to remove humic acids. In contrast, Gebbie (2001, p. 44) stated that ACH typically requires doses of 20 % of those for alum. The logarithmic relationship between raw water turbidity and coagulant dose indicated in Figure 5 and underlined by Spînu and Racoviteanu (2014, p. 14) was confirmed by Dearmont et al. (1998, p. 852), who found that chemical treatment costs increase at a decreasing rate as the level of raw water turbidity increases.

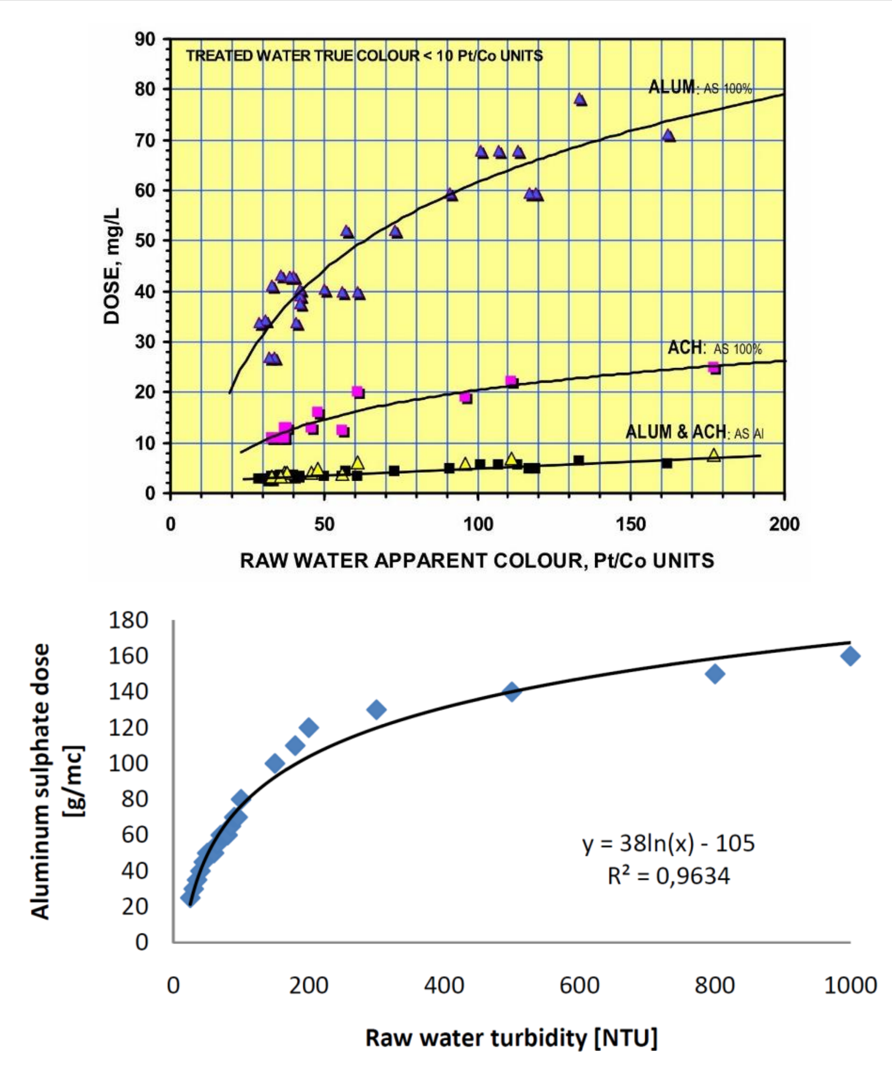

Figure 5: Empirical relationships between different raw water quality parameters and corresponding coagulant dose rates. The upper figure shows the relationship of raw water apparent colour and dose rates of alum, ACH, as well as a combination of both. The lower figure illustrates the relationship of raw water turbidity and alum dose rate. As the regression lines indicate, the functional relationship for each correlation was identified as logarithmic. Upper figure from Gebbie (2005, p. 78), lower figure from Spînu and Racoviteanu (2014).

2.3.3. Backwash water volumes

Crittenden et al. (2012, 728, 733) defined backwashing as the process of removing accumulated particles and solids from a filter bed by reversing the water flow. The authors expounded that any rapid filtration cycle consists of a filtration stage during which particles accumulate on the filter medium, and a backwash stage during which the accumulated material is flushed away from the medium by reversing the flow. The water used for the backwash stage is purified final water, usually extracted from the clear water well or final water tank at the DWTP (Crittenden et al. 2012, p. 734). According to Crittenden et al. (2012, 1633, 1642), filters are typically backwashed every 24 to 72 h and the backwash water usually makes up a volumetric share of 2 to 5 % of the total plant flow.

Singh and Mishra (2014, p. 74) stated that the frequency of filter backwashing as well as desludging of sedimentation tanks depends on raw water quality. Kraus Elsin et al.

(2010, p. 480) specified that higher raw water turbidity requires more frequent backwashing, which is associated with a partial stop of the filter process as well as electricity consumption to run the backwash pumps. According to Clark et al. (1985, p. 92), the length of time between filter backflushing cycles decreases at a decreasing rate as influent water turbidity increases, implying a logarithmic relationship. This suggests that electricity costs increase at a decreasing rate as well (Holmes 1988, p. 360).

For the case study DWTP evaluated by Heberling et al. (2015, p. 8744), the authors attributed an average of 84.3 % of the total power consumption to pumping. However, the backwash pumps were designated by the authors to have a relatively minimal electricity consumption in comparison to the raw/intake and final water pumps.

2.4. Impact of raw water quality on water treatment effort

2.4.1. General overview

Raw water quality is an important factor for planning and operation of water treatment plants. Crittenden et al. (2012, p. 13) identified the quality of the water source as one of the “most critical determinants in the selection of water treatment processes”. Price et al. (2017, p. 1) described source water quality as a “critical factor in utility design and operation” of water supply systems. The authors mentioned technology requirements, chemical treatment, dosing requirements, as well as monitoring practices to be affected by the source water quality. Plappally and Lienhard V (2013, p. 10) indicated that intake water quality determines the chemical usage in a water treatment system and is thus a “major reason of variation in treatment costs”. Inversely, the authors emphasise that exceptionally good raw water quality allows to neglect certain treatment steps such as coagulation and sedimentation, i.e., allow for direct filtration treatment.

As discussed in Chapter 2.2.3, sediments and particles may originate from various sources and be transported to surface water bodies on different pathways. If a DWTP uses surface water as raw water, it is confronted with these substances. Forster et al. (1987, p. 349) listed cropland soil erosion, storm runoff, industrial activities, streambank erosion, and other sources as potential factors for suspended sediments at a DWTP’s water intake. Warziniack et al. (2017, p. 17) mentioned weather conditions, soil or geology characteristics, agricultural practices, pesticide application, atmospheric deposition of nitrates, water hardness, and extreme events such as wildfires or landslides to affect treatment costs. According to Holmes (1988, p. 356), sediments in surface water used for drinking water treatment can lead to the requirement of sedimentation stages and increase expenditures on chemicals and filtration. For severe cases, the authors mentioned the need for special treatments to remove pesticides from the water. Furthermore, the authors associated the presence of pathogens due to soil erosion from agricultural fields with the requirement for disinfection at the DWTP.

While the described relationships are largely known in qualitative terms, the literature provides no universally accepted methodology to quantify the impact of raw water quality on water treatment effort. Some authors indicated that the exact impact of upstream land use on downstream water treatment remains poorly understood (Westling et al. 2020, p. 2; Vincent et al. 2016). Several descriptive studies provide empirical information on both raw water and operating parameters, and partly establish correlations between them. A selection will be discussed in Chapter 2.4.2.

Another set of studies established multiple regression modelling approaches to link source water quality to expenditures at DWTPs. A selection will be presented in Chapter 2.4.3. Such approaches promise a more comprehensive and accurate estimation of the impact of raw water quality on water treatment effort. Emphasis is placed on publications that include surface water turbidity as a water quality measure, and coagulant chemical use to describe treatment effort. The studies are presented as a basis to derive a multiple regression model for the case study DWTPs of the present thesis (research question III.) in Chapter 3.4.4.

2.4.2. Observations from descriptive studies

Sthiannopkao et al. (2006) and Sthiannopkao et al. (2007) discussed the situation in the Phong watershed in north-eastern Thailand that faces challenges similar to the SMMRB. Also here, a transformation from forestland to agricultural areas has occurred in the last few decades, resulting in about 64 % agricultural land use at the time of the studies (Sthiannopkao et al. 2006, p. 45). In conjunction with farming practices without soil conservation and encroachment of riverbanks, this land use causes severe soil erosion which is even aggravated by strong storms in the rainy season (Sthiannopkao et al. 2006, p. 45; Sthiannopkao et al. 2007, p. 706). The eroded material and attached substances such as nutrients and agricultural chemicals are transported to streams where they increase the amount of suspended solids, leading to average turbidity values of 8.87 NTU in the dry season and 316 NTU in the wet season (Sthiannopkao et al. 2006, p. 45; Sthiannopkao et al. 2007, p. 708). Furthermore, peak turbidities of 5,000 NTU in the upstream Phong River and 303 NTU at the intake of a case study DWTP were observed (Sthiannopkao et al. 2007, p. 710). According to the authors, fluctuations of raw water turbidity complicate water treatment and particularly alum dosing at the DWTP, resulting in an unstable final water quality. For the case study DWTP, Sthiannopkao et al. (2007,

p. 710) report of average alum dose rates varying between 28.46 mg/L in the dry season and 42.33 mg/L in the wet season. The temporal variability of raw water turbidity and alum dose rate for the observation period is shown in Figure 6. Furthermore, average backwash water volumes varied between 2,429 m³ and 3,206 m³ in the dry and wet seasons, respectively (Sthiannopkao et al. 2007, p. 710). In summary, soil erosion and resulting increased turbidity in surface waters are described by the authors as the "most serious problem" for the water supply utility in the watershed. Based on their findings, they recommended implementing an integrated land use management in the watershed to maintain good surface water quality and sustainability, which may as well lead to reduced water treatment costs.

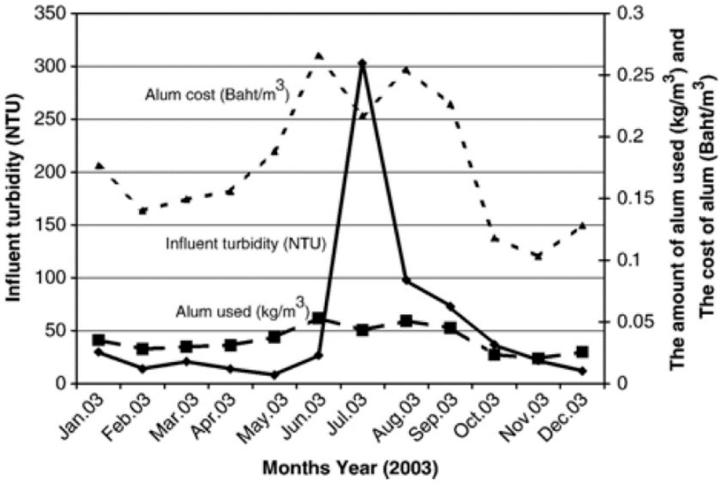

Figure 6: Temporal course of raw water turbidity, alum use, and alum costs at the case study DWTP investigated by Sthiannopkao et al. (2007).

Chang and Liao (2012) focused on natural factors inducing an inflow of sediments and particles into surface water bodies by establishing a rainfall intensity-raw water turbidity relationship for a case study water treatment plant in Northern Taiwan. The obtained relationship allowed the authors to predict raw water turbidity resulting from different rainfall intensities. For example, they calculated a turbidity of more than 5,000 NTU at the intake of the case study water treatment plant for rainfall intensities greater or equal to 165 mm/d, which had an exceedance probability of 10 %. According to the authors, highly turbid raw water with more than 5,000 NTU can adversely affect the operations of regular water treatment plants and increase the risk of shortfalls in water supply.

Also Lee et al. (2016) investigated turbidity concentrations in surface waters during and after extreme rainfall events for a case study area in Taiwan. The authors found that turbidity of surface waters is well correlated with both rainfall intensity and river flow rate for all events they evaluated. This confirms the findings of Chang and Liao (2012) described in the previous paragraph. Based on their results, Lee et al. (2016)

recommended improving basin management regulations to control river turbidity problems and preparing drinking treatment plants for adequate handling of high turbidity raw water with more than 2,000 NTU.

2.4.3. Multiple regression modelling and water-quality elasticities

Several studies examined the impact of raw water quality on water treatment effort using multiple regression modelling approaches, of which a selection is presented in the following. A unifying element of these studies is that they use costs to express the treatment effort by providing water-quality elasticities of cost, which are defined as the "percentage change in costs resulting from a 1 % change in source water quality" (Price and Heberling 2018, p. 199). Depending on the respective study, one or more water-quality elasticities were calculated that are either related to raw water quality parameters (e.g., turbidity, total organic carbon, pH), watershed loading (e.g., sediment load, phosphorus load, pesticide load), or land use classifications (e.g., percentage of forest, agricultural, urban, or other land uses in the relevant catchment area). Since the present thesis considers only water quality parameters to represent the intake water characteristics, studies that were mainly based on watershed loading (McDonald and Shemie 2014; Mosheim and Sickles 2021) and/or land use classifications (Abildtrup et al. 2013; Ernst et al. 2004; Fiquepron et al. 2013; Freeman et al. 2008; Mulatu et al. 2020; Price and Heberling 2020; Vincent et al. 2016) are not presented in detail. Furthermore, studies that were solely based on water quality parameters other than turbidity (Honey-Rosés et al. 2014; Horn 2011; Mosheim and Ribaudo 2017; Piper 2003) are not presented due to limited comparability to the modelling approach applied in this thesis.

It is worth mentioning that only one of the studies indicated above, namely Mulatu et al. (2020), investigated a study area in Africa, while the vast majority of research was conducted in North America. However, as Mulatu et al. (2020) focused on the importance of forest cover on chemical water treatment effort and do not include a water quality variable, their study takes a clearly different approach compared to the present thesis.

Remarkably, no universally accepted methodology to quantify the impact of raw water quality on water treatment effort has been established to date. All studies presented below are empirical examinations for individual DWTPs, sets of DWTPs, or one or more watersheds, applying a large variety of methodological approaches. Thereby, the results are not directly transferable to other study areas such as the SMMRB. In fact, Warziniack et al. (2017, 2, 15) stated that the nature of ecosystem dynamics, watershed processes, and water treatment technologies is complex, which make it elusive to measure the benefits of source water protection on water treatment and other areas.

Price and Heberling (2018) reviewed and synthesised 24 studies that established multiple regression modelling approaches to link source water quality to DWTP expenditures. 17 of the selected studies were based in North America, four in Asia and three in Europe, while none of the articles focused on a case study in Africa. The original publications show diverse research motivations, data characteristics, methodological analysis approaches, input parameters, and dependent variables for modelling. To allow for a comparison between the studies, Price and Heberling (2018) calculated the elasticities and corresponding standard errors (SE) for each study (if these were not already available). Following the authors, water quality measures can pertain to water parameters, watershed loading, or land use classifications, for which they calculated the respective elasticities accordingly (Price and Heberling 2018, p. 198). The findings indicate relatively large ranges of elasticities for most water quality parameters and land use classifications. Overall, turbidity was identified as the parameter the most commonly used in the reviewed studies as it is nearly universally monitored at DWTPs, while turbidity elasticities appeared to be the most robust since they were consistent despite the diverse data and analytical methods applied in the reviewed studies (Price and Heberling 2018, 198, 202). Nearly all turbidity elasticities were determined to be statistically significant with values in a range of -0.11 to 0.30 and a mean value of 0.14 (Price and Heberling 2018, p. 199). The latter implies that in average, a 1 % decrease in raw water turbidity leads to a 0.14 % reduction in treatment costs. For other parameters, the results were more varied and ambiguous. Overall, the authors conclude that marginal changes in water quality lead to statistically significant but modest savings in water treatment costs (Price and Heberling 2018, p. 202).

One of the studies included by Price and Heberling (2018) is a publication by Forster et al. (1987) focusing on soil erosion and its impact on water treatment costs. The authors analysed a panel data set of water quality parameters, soil erosion, and their impacts on surface water treatment in western Ohio, USA. The data set consists of data from twelve DWTPs for 25 months, summarising to 257 observations. In their model, the authors included turbidity improvement due to water treatment as well as sediment load as independent variables, while treatment plant size and storage time of the untreated water were included as control variables. Labour and maintenance were considered as constants. The parameter turbidity was used to represent rainfall, soil moisture, and season of the year (Forster et al. 1987, p. 350). As dependent variable, the authors chose average daily variable costs for water treatment, which consisted primarily of chemicals used in the treatment process. The results indicate an overall coefficient of determination (R^2) of 0.84, while all individual regression coefficients were statistically significant. The turbidity elasticity was calculated to 0.119 (SE = 0.043), implying that a 1 % decrease in raw water turbidity would lead to a 0.119 % reduction in treatment costs (Forster et al. 1987, p. 351).

Another study included in the review article described above was published by Moore and McCarl (1987). The authors focused on the off-site impacts of soil erosion by considering not only water treatment, but also other affected areas such as hydroelectric power generation, road drainage and river navigation maintenance, and reservoir capacity deterioration. Regarding water treatment, the authors analysed a time series data set with 963 daily observations from a surface water treatment plant in the Willamette Valley in north-western Oregon, USA (Moore and McCarl 1987, pp. 43–44). Based on this data set, the authors developed a multivariate model with two response variables, namely daily alum use and daily lime use, consequently including two multiple regression equations. For the dependent variable alum use, the authors used turbidity (to represent sediment load) and temperature as independent variables, and the volume of treated water as a control variable. The results of this analysis indicate an overall R^2 of 0.913 and a turbidity elasticity of 0.2193 (SE = 0.0152), implying that a 1 % decrease in raw water turbidity would lead to a 0.2193 % reduction in alum use per day (Moore and McCarl 1987, p. 45). The study by Moore and McCarl (1987) is the only study included in the review by Price and Heberling (2018) that relates raw water quality directly to coagulant use, which is pursued in this thesis as well.

Like Forster et al. (1987) and Moore and McCarl (1987), Holmes (1988) focused on the off-site impacts of soil erosion on water treatment. The author investigated a versatile data set including a survey of 430 public utilities in the USA published by the American Water Works Association in 1986, as well as several environmental, labour, and electricity related influencing factors (Holmes 1988, p. 362). Overall, the analysed cross-sectional data set comprised of 132 observations from surface water systems located all over the USA (Holmes 1988, p. 362). To analyse the data, the author developed a two-stage model, including a hedonic Cobb-Douglas cost function, and a spline function to establish a subsequent environmental linkage (Holmes 1988, p. 364). Of interest for the present thesis is the former, which includes influent water turbidity as independent variable, while treated water and expenditures on labour and electricity served as control variables (Holmes 1988, 361, 363). As dependent variable, the author chose expenditures for operation and maintenance per year with regard to a variety of areas of interest, with the goal to model the total costs of water production. The results indicate an overall R^2 of 0.84 for the model (Holmes 1988, p. 363). Source water turbidity was statistically significant at the 0.01 level with an elasticity of 0.07 (SE = 0.02), implying that a 1 %

decrease in raw water turbidity would lead to a 0.07 % reduction in expenditures on operation and maintenance (Holmes 1988, p. 363). Overall, the authors conclude that reduced sediment discharges would lead to relatively small estimated savings in the water treatment industry, adding that water treatment is only one of a variety of benefits from reduced soil erosion (Holmes 1988, p. 365).

Dearmont et al. (1998, p. 851) expanded the approaches from the previously discussed studies by including a dummy variable (dv) for chemical contamination in their modelling approach. The authors analysed a pooled cross-section time series data set on raw surface water quality as well as chemical costs of municipal surface water treatment in Texas, USA. The data originate from twelve DWTPs for a period of 45 months, summarising to 540 monthly observations. In their treatment cost model, the authors used the product of raw water turbidity and pH, as well as the mentioned dv (0-1) for potential chemical contamination, as independent variables. Treated water volume and precipitation were included as control variables. As dependent variable, the authors selected the costs for treatment chemicals (coagulants, disinfectants, and pH adjusters) to represent treatment effort. The multiple regression modelling approach established by Dearmont et al. (1998, p. 851) is:

$$\frac{cost}{1{,}000\ gallons} = b_0 + b_1 \times (total\ gallons) + b_2 \times (turbidity \times pH) + b_3 \times (turbidity \times pH)^2 + b_4 \times (turbidity \times pH)^3 + b_5 \times (contamination\ dummy) + b_6 \times (average\ annual\ rainfall) \quad (1)$$

The calculation results show that all regression coefficients (b_i) except for the cube of turbidity times pH were significant at the 95 % level. However, the R^2 of the overall model was at 0.1865 (Dearmont et al. 1998, p. 851), a value considerably lower than the R^2 values of the studies discussed before, indicating limited validity of the results. The authors calculated a turbidity elasticity of 0.27 (SE = 0.12), implying that a 1 % reduction in raw water turbidity would lead to a reduction in chemical costs of 0.27 % (Dearmont et al. 1998, p. 852). The elasticity of treated water volume was calculated to -0.04, implying that a 1 % decrease in treated water would increase chemical costs by 0.04 %, while the rainfall elasticity was at 1.74, implying that a 1 % decrease in average annual precipitation would lead to a decrease in cost of 1.74 % (Dearmont et al. 1998, p. 852). The authors note that the total estimated expenditures induced by surface water turbidity and chemical contamination would be higher if non-chemical costs were considered in the model as well (Dearmont et al. 1998, p. 852).

Forster and Murray (2007) expand the approaches by Forster et al. (1987), Holmes (1988), and Dearmont et al. (1998) by including two common agricultural practices, tillage and pesticide application, into their model. Thereby, the authors investigate the impact of pesticide use and farming practices on downstream water quality and water treatment costs. Like Forster et al. (1987), the study evaluates data from the state of Ohio, USA, namely from eleven communities in the Maumee River basin. The area is largely dominated by agriculture (88 % of land use), and prone to elevated uses of agricultural chemicals (Forster and Murray 2007, p. 116). As most communities in the river basin use surface water for their drinking water supply, the raw water has to undergo herbicide removal before use (Forster and Murray 2007, p. 116). The analysed panel data set consists of annual observations on plant characteristics, turbidity, and variable costs from eleven surface water treatment plants for the period 1995 to 1999, resulting in a total of 55 observations, as well as tillage, pesticide application, and soil erosion data (Forster and Murray 2007, pp. 121–122). To analyse the data, the authors developed a system of three equations (chemical cost function, variable cost function excluding chemicals, and turbidity function) to relate land use and farming practices to the resulting surface water turbidity and water treatment costs (Forster and Murray 2007, p. 119). Two of the equations were interlinked with each other as the values predicted by the turbidity function were used as independent values in the chemical cost function (Forster and Murray 2007, p. 123). Besides raw water turbidity, the chemical cost function includes pesticide load as independent variable, and volume of treated water as control variable (Forster and Murray 2007, p. 119):

$$\ln(annual\ chemical\ costs\ per\ water\ volume) = c_0 + c_1 \times \ln(water\ volume) + c_2 \times \ln(pesticide\ load) + c_3 \times \ln\ (turbidity) \qquad (2)$$

For this function, the results indicate an adjusted R^2 of 0.595 (Forster and Murray 2007, p. 124). Source water turbidity was statistically significant at the 5 % level, with an elasticity of 0.30 (SE = 0.08), implying that a 1 % decrease in raw water turbidity would lead to a 0.30 % reduction in expenditures on chemicals. The regression coefficients for treated water volume were determined to be statistically significant at the 5 % level as well, with elasticities of -0.17 for chemical costs and -0.41 for variable costs excluding chemical costs (Forster and Murray 2007, p. 124). The latter implies that a 1 % increase in produced water volumes would lead to a 0.41 % decrease in variable costs excluding chemicals, which is attributed by the authors to economies of scale (Forster and Murray 2007, p. 124).

Freeman et al. (2008) analysed a cross-sectional data set from 40 DWTPs in the USA. Their analysis included total organic carbon, different land use classifications, and a water quality index as independent variables and chemical water treatment costs per output and year as dependent variable. While the authors found an effect of total organic carbon on treatment costs, they were not able to identify an effect of surface water turbidity on treatment costs. This observation contradicts the other studies presented in this chapter.

Unlike the studies discussed so far, Abdul-Rahim and Mohd-Shahwahid (2011) examined a case study area outside of the USA. The authors investigated the impact of timber harvesting activities on the costs of water treatment in the federal state of Kelantan in Malaysia. Their panel data set contains daily raw water quality and water treatment data from six surface water treatment plants for a period of 48 weeks in the year 2009. Based on this, the authors calculated average values for different parameters that amount to a total of 144 two-weekly observations. Like Dearmont et al. (1998), Abdul-Rahim and Mohd-Shahwahid (2011) also used the product of raw water turbidity and pH as independent variable in their modelling approach. Furthermore, they included the volume of water produced, as well as a dv (0-1) for the influence of the seasonality as control variables. As dependent variable, average daily chemical costs per cubic meter of output over a two-week period was selected. The complete multiple regression modelling approach established by Abdul-Rahim and Mohd-Shahwahid (2011) is:

$$\ln\left(\frac{cost}{cubic\ meter}\right) = b_1 \times \ln(turbidity \times pH) + b_2 \times \ln(cubic\ meter\ treated) + dv_{precipitation} + \varepsilon_{it} \qquad (3)$$

The analysis results show an R^2 value of 0.68 for the model, which implies that 68 % of the variation of the dependent variable can be explained by the explanatory variables. The value is lower compared to the studies by Forster et al. (1987), Moore and McCarl (1987), and Holmes (1988), but considerably high than for the model by Dearmont et al. (1998). The regression coefficient for the product of raw water turbidity and pH was statistically significant at the 1 % level and the turbidity elasticity was at 0.07 (SE = 0.03), implying that a 1 % decrease in raw water turbidity would lead to a 0.07 % reduction in chemical costs (Abdul-Rahim and Mohd-Shahwahid 2011, p. 600). The coefficient for treated water volume was statistically significant as well, with an elasticity of -0.99 implying that a 1 % decrease in water volumes would increase chemical costs by 0.99 % (Abdul-Rahim and Mohd-Shahwahid 2011, p. 600). The elasticity for the dv representing seasonality was at 0.46, implying higher chemical costs during the wet season. However, the corresponding regression coefficient was not statistically significant (Abdul-Rahim and Mohd-Shahwahid 2011, p. 600). In summary, the authors attribute diminished surface water quality in the study area to logging activities and recommend the implementation of taxes for environmental pollution according to the polluter pays principle, with the goal of promoting logging practices with reduced environmental impacts (Abdul-Rahim and Mohd-Shahwahid 2011, p. 601).

Like Abdul-Rahim and Mohd-Shahwahid (2011), Singh and Mishra (2014) examined a case study area outside of the USA, namely the Western Ghats in the greater Mumbai region in India. The study examines the relationships between forest cover, surface water quality, and resulting water treatment costs in four watersheds dominated by forests and agricultural activity. Like Holmes (1988), the authors developed a two-stage model to estimate the recursive relationship between economic and environmental components, including one forest cover-turbidity relationship, and one turbidity-treatment cost relationship (Singh and Mishra 2014, p. 74). Of interest for the present thesis is the latter relationship, for which a time series data set from one surface water treatment plant in the study area was analysed, consisting of 144 monthly observations collected between 1995 and 2011. Based on this data, the authors developed a multivariate model with three response variables, namely monthly chemical costs, monthly operating costs (including chemicals, electricity, repairs and maintenance, and establishment and transport costs), and monthly water losses due to backwashing and desludging (Singh and Mishra 2014, p. 78). Consequently, the modelling approach includes three multiple regression equations. As control variables, the authors included the volume of treated water and lagged costs to establish a link between current and past costs. The results indicate a R^2 value of 0.66 for the chemical cost equation, with a statistically significant regression coefficient for turbidity ($p < 0.01$) (Singh and Mishra 2014, p. 80). The turbidity elasticity was determined to 0.203 (SE = 0.08), implying that a 1 % decrease in raw water turbidity would lead to a 0.203 % reduction in chemical costs (Singh and Mishra 2014, p. 80). The operating costs equation showed a R^2 value of 0.68. Also here, the regression coefficient for turbidity was significant, with an elasticity of 0.188 (SE = 0.07) (Singh and Mishra 2014, p. 80). The water loss equation showed a R^2 value of 0.66, with a statistically significant coefficient for turbidity and a turbidity elasticity of 0.06, implying that a 1 % decrease in raw water turbidity would lead to a 0.06 % decrease in water losses due to backwash and desludging (Singh and Mishra 2014, p. 80). In the chemical cost equation, the elasticity for treated water volume was at 0.06, implying, that a 1 % decrease in water volumes would decrease chemical costs by 0.06 % (Singh and Mishra 2014, p. 80). The authors conclude that if deforestation was avoided in the study area, the Municipal

Corporation of Greater Mumbai could save significant water treatment costs and mitigate the costs for development of a new water source (Singh and Mishra 2014, p. 73)

Heberling et al. (2015) took previous works including the treatment cost model by Dearmont et al. (1998) further and presented a comprehensive framework linking drinking water treatment costs to source watershed protection costs. The goal of the study was to determine the incentives for a water supply operator to invest in natural infrastructure or pollution reduction in the source watershed, rather than paying for water treatment at a DWTP (Heberling et al. 2015, p. 8741). Unlike the studies discussed previously, the authors included both short- and long-term relationships in their analysis by applying error correction models. Like Forster et al. (1987) and Forster and Murray (2007), the authors evaluated data from the state of Ohio, USA. The analysed time series data set contains 1,826 daily observations from one DWTP, collected between 2007 and 2011 (Heberling et al. 2015, 8741, 8746). As dependent variable, the author selected daily treatment costs per water output with regards to chemicals, pumping, and activated carbon costs (Heberling et al. 2015, 8741–8742, 8745). Independent variables include raw water turbidity, pH, UV_{254}, total phosphorus load, total organic carbon, and a dv for temperature, among others (Heberling et al. 2015, 8742–8743, 8748). Furthermore, a variety of control variables were included to account for scale effects (i.e., produced water volumes), seasonality, and lagged costs which are due to temporal delays between the timing of watershed loading events and their observation at the DWTP (Heberling et al. 2015, 8743, 8748). For different statistical approaches evaluated by the authors, the results indicated an overall R^2 of 0.61, which implies that 61 % of the variation of the dependent variable can be explained by the explanatory variables, respectively (Heberling et al. 2015, p. 8750). For turbidity, the calculated elasticities were statistically significant and indicated values of 0.02 (SE = 0.01) in the short run and 0.10 (SE = 0.05) in the long run, resulting in an overall turbidity elasticity of 0.11 (SE = 0.04) (Heberling et al. 2015, p. 8751). This implies that a 1 % decrease in raw water turbidity would immediately reduce treatment costs by 0.02 % and additionally by 0.1 % in the future, resulting in a reduction of 0.11 % over a five year period (Heberling et al. 2015, p. 8741). For the final water produced volumes, the authors calculated elasticities of -0.39 in the short run and -0.21 (SE = 0.11) in the future, resulting in an overall elasticity of -0.60 over a five year period (Heberling et al. 2015, p. 8751). For the case study area, the authors concluded that the costs for source watershed protection would be considerably greater than the obtained reduction in water treatment costs.

Price et al. (2017) performed a stochastic cost frontier analysis to evaluate the relationships between source water quality, variable water production costs, and cost efficiency.

The primary data base for their analysis is a census of Canadian municipal water providers published in 2011. The cross-sectional data base included information on source water quality, treatment technologies, plant capacities, and operating expenditures (Price et al. 2017, 1-2, 8). As in the studies discussed previously, the authors included only short-term variable costs in their analysis, and exclude capital responses to higher turbidity (Price et al. 2017, p. 10). The authors expanded the previously discussed modelling approaches by including the type of applied treatment technology to address differences in production efficiency, as well as the source water type to account for additional pumping efforts at groundwater systems (Price et al. 2017, pp. 1–2). As dependent variable, the authors chose the total annual costs for operation and maintenance related to the acquisition and treatment of source water, which includes materials (e.g., chemicals and spare parts), labour, and energy. Water quality is represented by the independent variable raw water turbidity, and several control variables were included to account for scale effects, factor prices, and type of applied treatment technology (Price et al. 2017, p. 4). For the latter, six 0-1 dv were used that depend on the type of treatment (Price et al. 2017, p. 4). Another 0-1 dv is included to differentiate the water source between surface water and groundwater (Price et al. 2017, p. 4). The results of the water quality-production cost relationship analysis show that source water turbidity is an important determinant of production costs (Price et al. 2017, p. 8). The overall turbidity elasticity was determined as 0.099 (SE = 0.021), implying that a 1 % decrease in raw water turbidity would lead to a 0.099 % reduction in variable costs (Price et al. 2017, pp. 7–8). When conventional treatment systems are considered separately, the results indicate a turbidity elasticity of 0.116 (SE = 0.026). In both cases, the corresponding regression coefficients were statistically significant ($p < 0.01$) (Price et al. 2017, p. 7).

Like Singh and Mishra (2014), Warziniack et al. (2017) focused on the impact of forest cover on chemical water treatment costs. Data for their analysis originate from a survey of American water utilities carried out in 2014, including annual data on water quality and treatment costs from 37 surface water systems in the USA, as well as land use data (Warziniack et al. 2017, 1, 7). Like Holmes (1988) and Singh and Mishra (2014), the authors developed a two-step process for the analysis, including an ecological production function relating land use to surface water quality, and an economic benefits function relating surface water quality to treatment costs (Warziniack et al. 2017, 1, 4). For the economic benefits function, the dependent variable was defined as the average chemical treatment costs per volume of treated water (Warziniack et al. 2017, p. 6). The authors considered an independent raw water quality variable (either turbidity or total organic carbon), and the volume of treated water as a control variable. Furthermore, like Price et al. (2017), the authors included the type of water treatment technology as control variables in the form of dummies (dv). The multiple regression modelling approach for the economic benefits function established by Warziniack et al. (2017, p. 6) is:

$$\ln\left(\frac{chemical\ treatment\ cost}{1{,}000\ cubic\ meter}\right) = \gamma_0 + \gamma_q \times \ln(water\ quality) + \gamma_v \times \ln(total\ volume\ produced) + \gamma_c \times dv_{conventional\ treatment} + \gamma_d \times dv_{direct\ filtration} + \gamma_a \times dv_{advanced\ treatment} + v_i \quad (4)$$

The results of the analysis by Warziniack et al. (2017) indicated an overall R^2 of 0.59, which implies that 59 % of the variation of the dependent variable can be explained by the explanatory variables. The regression coefficients were statistically significant for turbidity ($p < 0.1$) and treated water volume ($p < 0.05$) (Warziniack et al. 2017, p. 15). The turbidity elasticity was calculated by the authors to 0.19 (SE = 0.11), implying that a 1 % decrease in raw water turbidity would lead to a 0.19 % reduction in chemical water treatment costs. The elasticity for treated water volume was calculated to -0.19 (SE = 0.07), implying that a 1 % increase in water volume would lead to a 0.19 % reduction in chemical water treatment costs per output (Warziniack et al. 2017, p. 15). The authors attribute this finding to economies of scale with regards to cost savings from larger infrastructure and market power for chemical cost negotiations. With regards to land use, the results show that a 1 % increase in forest cover in a watershed would decrease surface water turbidity by 3 % (Warziniack et al. 2017, 13, 17). Furthermore, the authors find a high impact on turbidity from of grazing in the watershed, i.e., from additional agricultural activity per square kilometre.

A recently published study by Westling et al. (2020) investigated the effect of upstream land use and ecosystem functions on downstream drinking water production in Sweden. The authors analysed a panel data set consisting of land use, raw water quality, and chemical costs data for 76 municipal surface water treatment plants from the period 2000 to 2012 (Westling et al. 2020, p. 1). Water quality parameters of focus were E. coli to address human health impacts of land use, and turbidity. Like Warziniack et al. (2017), also Westling et al. (2020) used a two-step modelling approach for their data analysis, including the novel and recently modified empirical Generalised Method of Moments estimator to link land use to surface water quality, and a regression analysis with the same method to estimate the chemical costs of treating surface water. The authors further controlled for confounding factors between treatment plants as well as over time. In their chemical cost function, Westling et al. (2020, p. 3) included a matrix of average water quality parameters (Q_{iy}), treated water volume (vol_{iy}), and total annual rainfall in the area closest to the treatment plant (r_{iy}) as independent variable to explain the dependent variable annual chemical costs per unit of treated water (C_{iy}). The chemical cost function established by the authors is:

$$\ln(C_{iy}) = \beta_1 \times \ln(Q_{iy}) + \beta_2 \times \ln(vol_{iy}) + \beta_3 \times \ln(r_{iy}) + v_i + \theta_y + \varepsilon_{iy} \quad (5)$$

The results of the analysis by Westling et al. (2020, p. 7) indicated statistically significant regression coefficients for turbidity, rainfall (both $p < 0.05$), and treated water volume ($p < 0.01$). The findings showed that upstream land uses considerably affect downstream water turbidity, and that increasing turbidity levels increase treatment costs. The turbidity elasticity was calculated to 0.285 (SE = 0.122), implying that a 1 % decrease in raw water turbidity would lead to a 0.285 % reduction in chemical water treatment costs. The elasticity for treated water volume was calculated to -0.293 (SE = 0.0562), implying that a 1 % increase in water volume would lead to a 0.293 % reduction in chemical water treatment costs per output (Westling et al. 2020, p. 7). The authors attributed this finding to a benefit of scale. For precipitation, the regression coefficient was calculated to 0.807 (SE = 0.380). Westling et al. (2020, p. 7) interpreted this as follows: “The estimated elasticity of approximately 0.8 means that a year during which rainfall is 1% above average, chemical costs can be expected to be 0.8% above average.” According to the authors, precipitation variations due to climate change may have considerably consequences in this context. The authors concluded that decision makers should not only invest in water treatment equipment, but also consider investments in upstream ecosystems.

2.5. Gap in the literature

As Price and Heberling (2018) pointed out, the impact of source water quality on water treatment effort has been studied comprehensively for case studies from high- and middle-income economies in North America, Asia, and Europe. Remarkably, no study relating water quality to water treatment effort has been undertaken on the African continent to date.

To address this knowledge gap, the present thesis will investigate the impact of surface water quality variations on treatment effort for a river basin in East Africa. By this, the report will further add knowledge to the body of literature for the SMMRB, which may support local decision-making.

2.6. Conceptual framework

To summarise and synthesise the information from the literature presented before and transfer it to the present research, the conceptual framework applied in this thesis is shown in Figure 7. The framework breaks the abundant and complex processes in a river basin down to three key areas of interest as well as the interconnections between them. Furthermore, the framework indicates where key outputs associated with the research questions (see Chapter 1.2) will be derived.

The chain of thought starts with sources and mobilising factors of sediments and particles in a river basin, in this case the SMMRB. Different diffuse and point sources of substances are acknowledged, which were however not included as concrete parameters in the present work. Mobilising factors of sediments were included in the form of two precipitation related parameters, namely total rainfall, and seasonality. As a reaction to these two factors, stream water quality in the river basin is assumed to vary in line with the framework established by Granger et al. (2010). In the present thesis, water quality is expressed exclusively by parameters related to sediments and particles, namely apparent colour and turbidity. Furthermore, it is assumed that stream water quality is the key influencing factor for variations in treatment effort at the case study DWTPs, while the sources and mobilising factors have certain direct effects as well.

To identify suitable parameters to represent treatment effort at the DWTPs, key input streams to the facilities were determined based on their schematic setups (see Chapter 4.1) as well as background knowledge from the literature. As mentioned earlier, only parameters that are potentially influenced by varying raw water quality were taken into consideration, i.e., specific variable input factors required for water treatment. Though changes in water quality can affect the level of investment in DWTPs in the long run (Holmes 1988, p. 361; Warziniack et al. 2017, p. 16), fixed inputs such as capital investments, labour, or administrative expenditures were assumed not to change significantly due to variations in raw water quality during or directly after the study period, which is in line with Forster and Murray (2007, p. 116) and Singh and Mishra (2014, p. 78). Therefore, fixed inputs were not considered in the present study. Some variable input factors such as repairs and replacements, as well as other support processes to operate the DWTP (Plappally and Lienhard V 2013, p. 12), could not be considered due to missing data.

The identified parameters to represent treatment effort at the DWTPs are coagulant chemical use, disinfectant chemical use, and energy consumption. For the event that energy consumption data were not sufficiently available, also backwash water volumes were analysed as a potential proxy variable to represent energy consumption. Some of the mentioned parameters were discarded to represent variable treatment effort during the analysis due to limited data availability, or as they do not effectively represent varying treatment effort due to raw water quality changes (see Chapter 3.4.4). Between all described key areas of interest, empirical relationships were assumed as shown in the turquoise box at the bottom of Figure 7.

Due to lack of information and data, as well as the limited scope of the present research as defined in Chapter 1.2, several potential influencing factors were not considered in this thesis. These include factors related to the sources of sediments in the SMMRB (i.e., regarding diffuse sources such as land cover, use, and management, as well as point sources such as industrial or municipal waste(-water) discharges); and certain variable input factors at the DWTPs as stated above (e.g., repairs and maintenance). Temporal factors affecting the transport of substances to surface water bodies (i.e., lagging effects, delays, and time lags of the runoff wave) were considered only to a limited extent with the parameter seasonality, and have not been studied extensively.

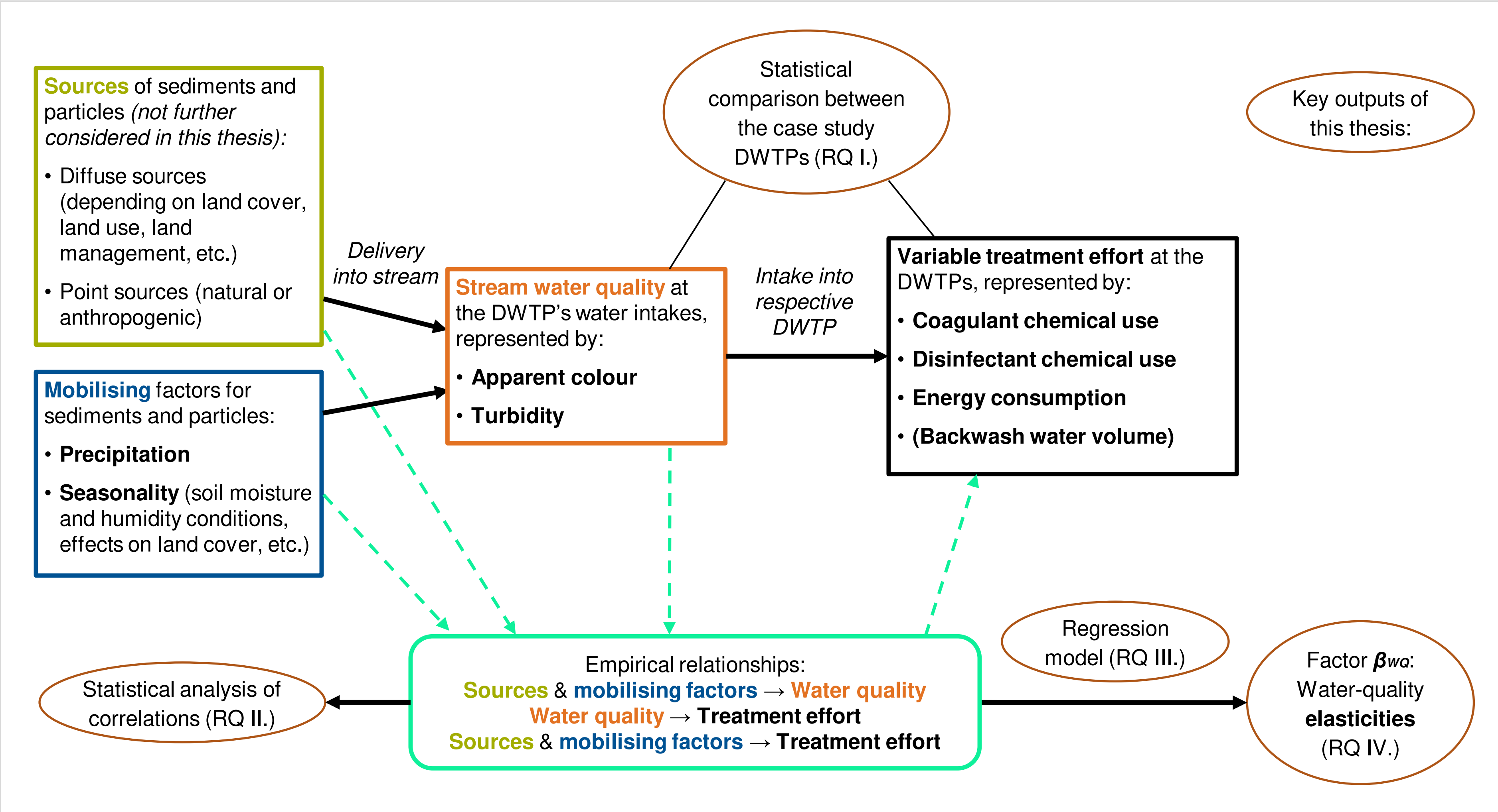

Figure 7: Conceptual framework applied in this thesis. Indicated in ellipses are the pursued key outputs of this thesis, assigned to the respective research questions (RQ) they belong to.

3. Data and methods

3.1. Description of the case study DWTPs (data origin)

As described in Chapter 1.2, the present thesis focuses on three case study water supply schemes within the SMMRB. The schemes are located on the Ugandan side of the river basin along river Lwakhakha, Malaba, or their tributaries, use surface water (i.e., stream water) as raw water, and are operated by the Ugandan public utility company NWSC. In administrative terms, all three schemes are assigned to the eastern & northern region of NWSC (NWSC 2018, p. 13). For further information on the river basin, including its hydrology and the general structure of drinking water supply, see Chapter 2.1. The case study water supply schemes are Lirima Gravity Supply Scheme (referred to as "Lirima"), Sono Gravity Supply Scheme ("Sono"), and Malaba-Tororo Water Supply ("Malaba-Tororo"). Figure 8 shows the locations of the water supply schemes' DWTPs within the SMMRB. Table 1 includes administrative and geographical information on the three schemes and their DWTPs. Further information on the case study DWTPs, including their treatment approaches and evaluations of relevant parameters, is provided in Chapter 4.1. Appendix E presents a selection of photos of the water supply schemes.

Lirima is a gravity flow piped water system in Bukhoho sub-county, Namisindwa district (The Infrastructure Magazine 2018). It is located on the slopes of Mount Elgon, in the proximity of Mount Elgon National Park. The sole raw water source for the DWTP is river Lirima, a tributary of river Lwakhakha (Government of Uganda 2020, p. 33). The designed water abstraction of the DWTP is 6,328 m^3/d, while the minimum flow of river Lirima at the point of intake is at 36,028 m^3/d (Government of Uganda 2019, p. 31). The scheme is a centrally implemented development project managed by the MWE through its Rural Water Supply and Sanitation Department (Government of Uganda 2020, p. 31). Its implementation began in 2010, construction works commenced in 2013 (Government of Uganda 2013, p. 42). The scheme was funded by the African Development Bank and the Government of Uganda under the Water Supply and Sanitation Programmes I and II (The Infrastructure Magazine 2018). While phase I is completed and fully operated by NWSC, the goals of phase II were achieved by 95 % in 2020 (Government of Uganda 2020, p. 33). According to Watala (2018), Lirima has a connection size of 31,804. In contrast, the MWE stated that 179,000 people from 1,700 households are targeted for supply by the scheme (Government of Uganda 2019, p. 31). Lirima supplies several sub-counties in the districts of Manafwa, Mbale, and Tororo (The Infrastructure Magazine

2018). Ugandan President Museveni stated that 40 % of the drinking water produced by Lirima should be supplied for domestic purposes, while 60 % are foreseen for agricultural irrigation (PPU REPORTER 2018).

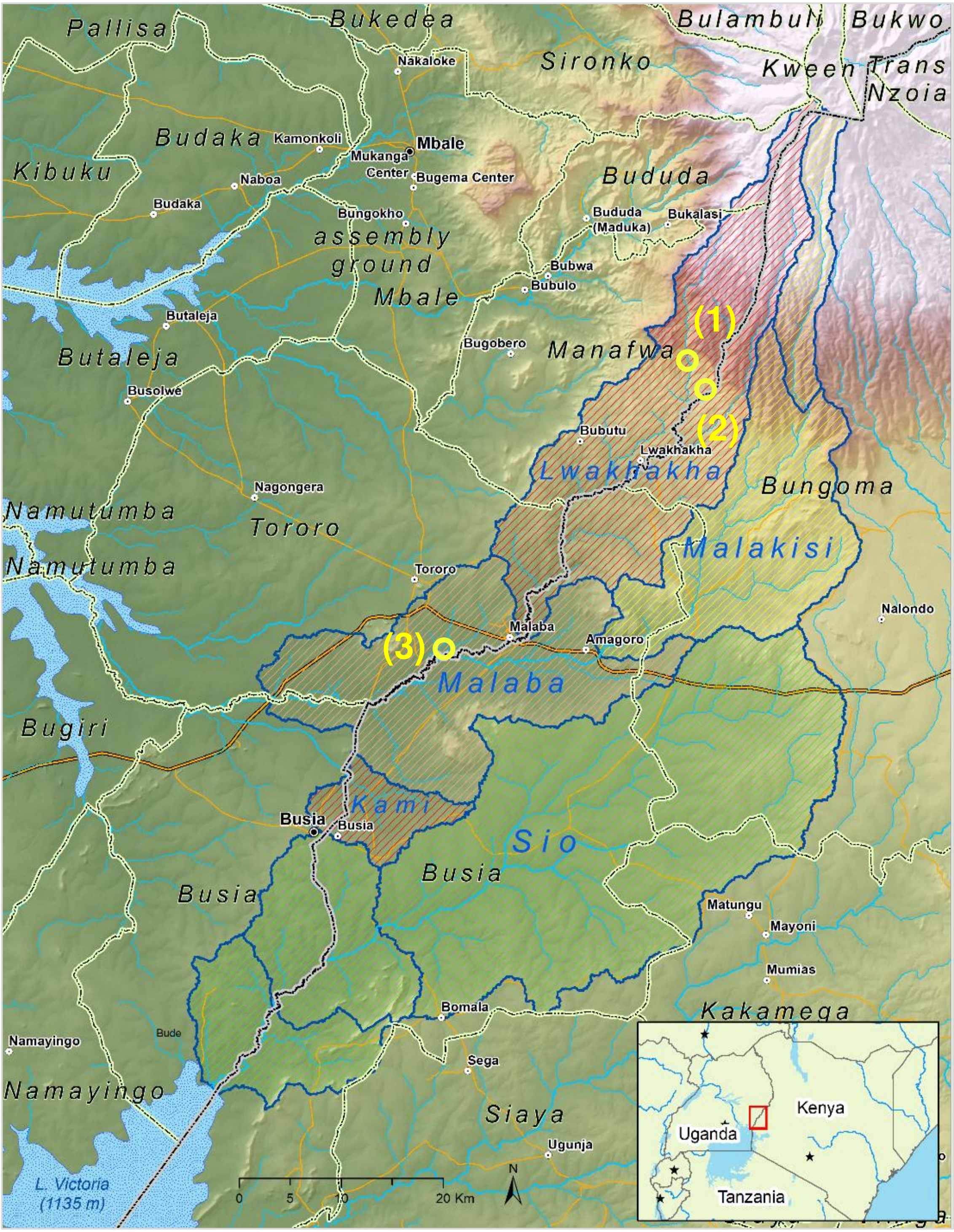

Figure 8: Sub watersheds of the SMMRB and locations of the case study DWTPs, namely (1) Lirima, (2) Sono, and (3) Malaba-Tororo. Map from Herrnegger (1/31/2020), yellow markings added by the author.

	Lirima	Sono	Malaba-Tororo
Official name of DWTP	Lirima Gravity Water Treatment Plant	Sono Gravity Water Treatment Plant; Manafwa-Tororo Gravity Flow Scheme	Malaba Water Treatment Plant
Position of DWTP	0°53'16.3"N 34°24'43.7"E	0°51'22.9"N 34°26'36.0"E	0°37'47.5"N 34°12'18.8"E
District	Namisindwa (since July 2017; before: Manafwa)	Namisindwa (since July 2017; before: Manafwa)	Tororo
Main watershed	Upper Malaba	Upper Malaba	Malaba
Sub watershed	Lwakhakha-Malaba sub watershed	Lwakhakha-Malaba sub watershed	Malaba-Malakisi sub watershed
Source stream	River Lirima (tributary to river Lwakhakha)	River Lwakhakha (tributary to river Malaba)	River Malaba
Connection size (according to plant overseers)	Appr. 50,000 people	Appr. 45,000 people	Appr. 150,000 people
Position of water intake	0°54'08.6"N 34°25'04.5"E	0°51'32.6"N 34°26'40.6"E	0°37'31.7"N 34°12'24.8"E
Relevant parameters for area upstream of water intake (mean values)	Area: 43.0 km² Rainfall: 1,763 mm/a Elevation: 2,566 m Slope: 13.0°	Area: 93.5 km² Rainfall: 1,774 mm/a Elevation: 2,849 m Slope: 12.6°	Area: 1,203.4 km² Rainfall: 1,703 mm/a Elevation: 1,761 m Slope: 6.6°
Plant overseer/Quality control officer	Tito Amuku (26th December 2017 to 1st August 2020)	Sarah Mbabazi (since middle of 2018)	John Ogire

Table 1: Geographical, administrative, and hydrological information on the case study water supply schemes. Based on personal notes from the study area, except for information on main and sub watersheds by Stecher and Herrnegger (2019), and information on relevant upstream areas of water intakes by Herrnegger (2020).

The DWTP of Sono is located about 4.9 km downstream from Lirima. Just like Lirima, it is located on the slopes of Mount Elgon in the vicinity of the border to Kenya (Among 2018). Its raw water originates from river Lwakhakha. According to Juma (2011), Sono was initially constructed by railway authorities in the 1950s/60s to supply water for steam engines at the Tororo railway station. After being abandoned for years, it was rehabilitated and redesigned by the Government of Uganda and MWE (Juma 2011) and commissioned in 2010. According to Juma (2011), Sono has a connection size of more than 39,000 people and supplies drinking water to several sub-counties in the districts of

Manafwa and Tororo. Among (2018) mentioned that the plant serves Namisindwa district as well. In October 2018, Sono's DWTP and water pipe network were damaged by landslides and land movements, followed by an acute water shortage in the supply area (Daily Monitor 2018).

About 36.5 km further downstream from Sono is the DWTP of Malaba-Tororo. It is located about 5 km southeast of the district headquarter Tororo town, and in immediate vicinity of the border to Kenya. Its raw water originates from river Malaba, after its confluence with river Malakisi that occurs about 1.2 km upstream of the plant's water intake. Due to its location in the Malaba-Malakisi sub watershed, the relevant upstream area of Malaba-Tororo is bigger and leads to different water quality challenges compared to Lirima and Sono. The DWTP consists of two treatment lines operated in parallel. The old line is in operation since 1956, while the new line was added in 1988.

The general procedure for documenting daily water quality and operating parameters is comparable in the three DWTPs. In terms of water quality, several parameters are measured by plant staff in the respective on-site laboratories. These include pH, electrical conductivity, apparent colour, turbidity, total alkalinity, total hardness, aluminium residual (not at Malaba-Tororo), free residual chlorine, and total residual chlorine. Most measurements are carried out once per day in the morning; for some parameters at individual plants, a second measurement is carried out in the afternoon. Total hardness and total alkalinity are measured once per week. At Malaba-Tororo, also microbiological parameters, e.g., faecal coliforms and E. coli, are measured once per week. The measurements are performed with grab samples taken at different points in the treatment trains, namely with raw water, water after clarification, water after filtration, and water after disinfection, i.e., final water. The daily results from the water quality analyses are recorded by hand in so-called Physico Chemical Result Books (Lirima, Sono) or evaluation sheets called "Physico-Chemical Characteristics" (Malaba-Tororo) (see Table 2, record categories i and ii). At the end of each month, all handwritten values are transferred to Excel sheets, from which monthly average values are calculated (see Table 2, record categories viii and ix). In addition to these daily measurements, monthly and quarterly water quality analyses are performed in the regional NWSC laboratory in Mbale town, Mbale district, with the aim to verify the on-site test results. The same parameters as described above are evaluated, plus TSS, total iron, and microbiological parameters. Water samples originate only from raw and final water. The results are compiled individually for each DWTP in monthly reports on physico-chemical water quality analyses (see Table 2, record category iii). Quarterly analyses, also called audits, are performed at the central NWSC laboratory in Kampala with samples from all water supply schemes in the Eastern region, including from raw water, final treated water, and network or reservoir water. Besides the parameters described above, also heavy metals and pesticides are measured. However, the analyses were not available for this research.

In terms of operating parameters, different daily water volumes and chemical uses are recorded by the respective plant staff. Water volumes include raw water pumped[3], final water produced, and service water or backwash water. These are calculated based on daily volume differences from the meter readings at the DWTP's pumps. All values are recorded by hand in record books called "Daily Pumpage Register" (Lirima), "Pumpages and Chemical Used" (Sono), or evaluation sheets called "Daily Chemical Consumption" (Malaba-Tororo) (see Table 2, record categories ii and iv). Here, also daily chemical uses regarding coagulant and disinfectant chemicals are recorded. Furthermore, reports on energy consumption are compiled by the plant engineers. However, these were not or only to a very limited extent available for this research.

The biggest share of data analysed in the subsequent chapters originates from the case study DWTPs of Lirima, Sono, and Malaba-Tororo and was created by NWSC staff according to the procedures described before.

3.2. Data collection

The data used for the present thesis was largely collected during a research stay in Uganda and Kenya in early 2020, as well as during subsequent electronic communication via email and messaging services with partners from NWSC. The research stay took place from 25th January to 8th February 2020 and was funded by the Friedrich Ebert Stiftung Academic Foundation. Goals included getting familiar with the study area, establishing relevant professional contacts, performing site visits to the case study DWTPs, receiving data required for the research, and participating in three stakeholder workshops from the CapNex project. Following the research stay, additional information and data was provided by NWSC in cooperation with the Department for Water Quality Management and the Department for Research & Development. More detailed information on the data collection, as well as a list of relevant contact persons, is provided in Appendix A. Furthermore, precipitation data for the SMMRB was provided by Dr. Mathew

[3] The designation "raw water pumped" will be used consistently in this thesis to describe the intake water stream that enters a DWTP, regardless of whether the water is pumped, or flows into the plant by gravity.

Herrnegger, including data for the relevant upstream areas of five selected DWTPs in the river basin.

3.3. Data description

The following qualitative information and visual material was obtained during the research stay or subsequent communication:

- Personal notes taken by the author during the research. These include expert interviews with NWSC staff, general information from the site visits, plant designs, and notes from the stakeholder workshops.

- Photo and video documentation of Lirima, Sono and Malaba-Tororo DWTPs, their water intakes and the corresponding streams, taken during the research stay in the study area. Altogether, 702 photos and 47 videos were made by the author and photographer Elias Okemer. Appendix E presents a selection of photos.

- Expert interviews with Moses Butele (see Appendix C) and John Ogire (see Appendix D), performed in May and June 2020 via telephone calls, emails, and messaging services.

NWSC provided also quantitative data on the case study water supply schemes in both hard copy and digital form, as shown in Table 2. For the former, detailed plant recordings were handed over to the author during the research stay from which photocopies were made. Data in digital form was provided as Excel files via email or USB sticks. Besides this, quantitative data on precipitation in the SMMRB was provided by Dr. Mathew Herrnegger in digital form. The data originates from the CHIRPS satellite precipitation data base and includes the period 1stJanuary 1981 to 31st December 2019 in both daily and monthly resolution. Based on the raw data, precipitation in the relevant upstream areas of five selected DWTPs was calculated according to Herrnegger (2020). These include the case study DWTPs Lirima, Sono, and Malaba-Tororo. A detailed description of all quantitative data provided for this thesis is included in Appendix A.

Combined, the data result in a panel data set, i.e., a data set that follows a given sample of individuals (here: DWTPs) over time and provides multiple observations (here: precipitation, raw water quality, and operating parameters) on each individual in the sample (Hsiao 2003, p. 1). Appendix B delineates the procedure of data preparation, error corrections, and assumptions made to obtain a usable data basis that allows to pursue the research objectives of this thesis.

Record category	Title	Format	Relevant parameters	Temporal resolution	DWTPs and periods covered	Digitised in author's Excel file?
Quantitative data in hard copy form						
i	"Physico Chemical Result Book"	Record books (hard copies, 498 pages)	Apparent colour, turbidity	Daily	Lirima • 29th November 2017 to 12th March 2018 • 19th March to 28th July 2018 • 1st September to 22nd November 2018 • 1st January to 31st April 2019 Sono • 3rd July to 5th December 2018 • 7th December 2018 to 28th April 2019 • 27th September 2019 to 30th January 2020	Yes, the relevant parameters
ii	Monthly data collections	Data sheets and summary reports stapled together (hard copies, 280 pages)	Apparent colour, turbidity, raw water pumped, final water produced, service water, coagulant used (ACH)	Daily, monthly	Malaba-Tororo • January 2017 to January 2018 • March to November 2018 • December 2017 to January 2019 (only handwritten summary notes)	Yes, the relevant parameters, and chlorine used

iii	"Report on Physio-Chemical Water Quality Analysis" / "Water quality for selected points in Tororo area"	Data sheets (hard copies, 28 pages)	Apparent colour, turbidity	Individual days	Lirima • Sampling dates: 24th January, 27th February, 20th March, 26th April, 20th July 2019 Lirima and Sono • Sampling dates: 27th October, 24th November, 18th December 2017 Sono • Sampling dates: 24th January, 27th February, 20th March, 26th April, 20th July 2019 Malaba-Tororo • Sampling dates: 30th October, 13th December 2016, 24th January, 21st February, 24th March, 7th April, 25th May, 23rd June, 24th October, 28th November, 13th December 2017, 24th October, 28th November, 18th December 2018	Yes, only used in Table 4
iv	"Daily Pumpage Register" / "Pumpages and Chemical used"	Record books (hard copies, 110 pages)	Raw water pumped, final water produced, service water, coagulant used (alum or ACH), coagulant dose rates	Daily	Lirima • 18th September 2016 to 1st March 2018 Sono • 3rd July 2018 to 2nd February 2020 Malaba-Tororo • 27th September 2017 to 30th November 2018 • 1st December 2018 to 31st January 2020	Yes, the relevant parameters, and chlorine used
v	"Determination of polymer/alum dose rate"	Evaluation sheets (hard copies, 12 pages)	Turbidity, optimum alum dose rate	Individual days	Lirima • 12 individual jar test experiments between April and July 2018	No

vi	"Tax invoices" of electricity consumption	Invoices (hard copies, 8 pages)	Electricity consumption	Monthly	Malaba-Tororo • July to September 2018 • May to July 2019 • September 2019 • November 2019	Yes, but not used in this thesis
vii	Fuel orders record book	Record book (hard copies, 20 pages)	Petrol fuel orders, diesel fuel orders	Individual days	All case study DWTPs • Individual days from 2018 to 2020	No, not legible
Quantitative data in digital form						
viii	Quarterly reporting for the Eastern Region	Summary reports (8 Excel files)	Apparent colour, turbidity, raw water pumped, final water produced, coagulant used (alum and ACH), coagulant dose rates	Monthly	25 DWTPs, among them all case study DWTPs • January 2018 to December 2019	Yes, the relevant parameters, and chlorine used
ix	Monthly reporting for the Eastern Region	Summary reports (2 Excel files)	Apparent colour, turbidity, raw water pumped, final water produced, coagulant used (alum and ACH), coagulant dose rates	Monthly	22 DWTPs, among them all case study DWTPs • October 2017 • December 2017	Yes, the relevant parameters, and chlorine used

Table 2: Overview of quantitative data provided by NWSC for the present research. The record categories i to ix were defined by the author to facilitate referencing to the data in subsequent chapters.

3.4. Methodology

To establish the link between stream water quality and treatment effort in the SMMRB and to address the research questions described in Chapter 1.2, the data and information acquired during the research stay and the subsequent communication were evaluated. For this, a series of analyses with descriptive, explanatory, and exploratory elements was conducted, as described in the following. While focusing on the case study DWTPs introduced in Chapter 3.1, the findings are assumed to be representative of the study area with regards to general conclusions and qualitative statements about the parameters. Thereby, conclusions and recommendations for the whole SMMRB were derived.

3.4.1. Comparison of the case study DWTPs

Based on information acquired during the research stay and subsequent expert interviews, the case study DWTPs and their respective water treatment approaches were described and schematically visualised (see Chapter 4.1). The available visual material, mainly photos and videos, was reviewed, and selected photos were compiled into a photo documentation of the study area and the case study DWTPs (see Appendix E).

To obtain a general overview of water quality at the case study schemes, selected raw and final water quality parameters were compiled (see Table 4) based on average values calculated from the evaluation sheets on water quality (see Table 2, record category iii). The individual values were presented after a formal outlier analysis, as described for example in Sperling et al. (2020, pp. 125–128). This approach to identify and exclude outliers was used consistently throughout this thesis, wherever noted.

3.4.2. Evaluation of raw water quality and operating parameters

<u>Selection of relevant parameters</u>

To obtain a quantitative data base allowing for a series of computer-aided evaluations (e.g., calculation of statistical parameters, simple and multiple regression analyses, visualisations), a selection of the quantitative data described in Table 2 was digitised and merged into an Excel file. The selection was made based on prior knowledge from the literature as well as discussions with academic supervisors and peer researchers. Mainly parameters that are part of the scope of analysis for this thesis were included, as defined in the conceptual framework in Chapter 2.6. They belong to the presence of sediments and particles in stream water, as well as their corresponding removal processes. Furthermore, operating parameters of general relevance were considered in an initial step with regards to processed water volumes, disinfectant chemical use, and energy consumption. The selected parameters are:

Parameter	Group
(1) Raw water apparent colour (in PtCo) (2) Raw water turbidity (in NTU)	Representing raw water quality
(3) Raw water pumped (in m³) (4) Final water produced (in m³)	Required for calculations
(5) Service water (in m³) (6) Coagulant (alum or ACH) use (in kg)	Representing variable treatment effort
(7) Disinfectant (chlorine) use (in kg) (8) Energy consumption (kWh or kg fuel)	Digitised, but not further considered

Parameters (1) and (2) were included to represent raw water quality related to sediments and particles at the intakes of the case study DWTPs. Parameters (3) and (4) were selected as they are required to assess activity at and production capacity of the DWTPs, as well as for further calculations (e.g., of chemical dosing concentrations). Parameters (5) and (6) were selected as they represent variations in variable treatment effort as a response to varying raw water quality. Since higher contents of sediments and particles in raw water increase the frequency of backwashing of filters and cleaning of sedimentation tanks (see Chapter 2.3.3), parameter (5) was selected as it entails water uses for both purposes. Parameter (6) was selected since the application of coagulant chemicals is a central component of sediment and particle removal in conventional water treatment (see Chapter 2.3.1).

The quantitative data base also included data on (7) disinfectant chemical use and (8) energy consumption which are both components of the variable treatment effort at the case study DWTPs. Hence, available values for both parameters were digitised and analysed as well. However, it was determined that parameter (7) was not affected by varying raw water qualities, which goes in line with findings from the literature (see Chapter 2.3.1). As the parameter thus does not directly serve the research questions of the present thesis described in Chapter 1.2, its data series were not further considered for the evaluation. Regarding parameter (8), the quantitative data base contained only few and fragmented data. For Lirima and Sono, the available data was limited to constant weekly estimates, while for Malaba-Tororo, eight monthly electricity consumption values were provided. Based on these, it was not possible to establish daily or weekly data series for electricity consumption. Therefore, the data series was not considered for evaluation in the present thesis as well. In summary, only qualitative information on both disinfectant chemical use and energy consumption were included in the description of the case study DWTPs (see Chapter 4.1), while the quantitative data was excluded for the further evaluations.

Besides these, no other parameters from the quantitative data base were considered in this thesis (e.g., water quality parameters such as pH, electrical conductivity, total alkalinity, total hardness, total iron, free chlorine, total residual chlorine, and residual aluminium). Furthermore, only raw water qualities were taken into account, while analysis results from other sample points within the treatment trains (e.g., water after sedimentation, after filtration, final water) were not included. Both decisions were made either due to limited data availability, due to distrust in the data's credibility, or due to the impression that the parameters did not serve to answer the research questions.

In addition to the described parameters from the NWSC data sets, precipitation data for the SMMRB was considered as well. In summary, this resulted in a total of seven quantitative parameters that were further investigated in this thesis, i.e., parameters (1) to (6), as well as precipitation.

<u>Definition of data resolution and observation period</u>

As illustrated in Table 2, data in both daily and monthly resolution was provided for the selected parameters. From the hard copies, record categories i, ii, and iv contain daily data, vi contains monthly data, and iii, v, and vii contain data for individual points in time. Within the digital data, the precipitation data set contains daily data, while record categories viii and ix contain monthly data. Hence, daily data was predominantly available in the form of handwritten record sheets. From these, a higher reliability, credibility, and the absence of transfer errors due to digital copying of data can be expected compared to digital data. Furthermore, a daily resolution allows to analyse and evaluate data based on a bigger number of data points, which increases the informative value of the analysis. Due to both reasons, it was decided that daily resolution data should generally be used with priority in this thesis compared to data in monthly resolution. However, monthly data, either provided from the quarterly or monthly reporting by NWSC, or calculated by the author based on daily data, was analysed as well. A monthly resolution allows for a better overview of the temporal course of parameters at the case study DWTPs and might compensate for random errors and outliers, which are present in the daily data. Therefore, data in both daily and monthly resolution were chosen for examination of the selected parameters.

An assessment of the temporal availability of daily data for parameters (1) to (7)[4] is shown in Table 3. While a comparatively good data availability can be observed for Malaba-Tororo, the table also illustrates that substantial gaps exist in most other data series. There is not a single month where all seven parameters for the three DWTPs are available at the same time. Against the background of this rather poor data availability, it was decided that the observation period of the present study should be defined as broad as the data allows, since all suitable quantitative data would increase the informative value of the evaluation. Hence, the general observation period was defined to last from 18th September 2016 to 31st January 2020, i.e., from the first day with available data to the last. For individual DWTPs, the observation periods may vary, as Table 3 shows.

Digitisation and preparation of data

After this preliminary work (i.e., selection of relevant quantitative parameters as well as definition of prioritised resolutions and observation period), the above-mentioned digitisation of hard copy data was carried out. For this, an Excel file titled "CapNex_Analysis_2016-2019_David-Mondorf" was created (hereinafter referred to as the author's Excel file), in which all activities described below were carried out. The Excel file is available as a supplement to this thesis. Since daily precipitation data for the respective relevant upstream areas of the case study DWTPs was already available in digital form, it did not require further editing by the author. All other daily resolution data was provided by NWSC in hard copy form (see Table 2, record categories i, ii, and iv). For each case study DWTP, the corresponding daily data for parameters (1) to (7) were digitised manually into the author's Excel file.

[4] Parameter (7), disinfectant chemical use, was not considered in further evaluations of this thesis but digitised and analysed in an initial step to check for potential correlations with varying raw water qualities.

DWTP	Lirima							Sono							Malaba-Tororo						
Para-meter / Month/year	1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7
09/16																					
10/16																					
11/16																					
12/16																					
01/17																					
02/17																					
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Table 3: Availability of daily data on seven selected raw water quality and operating parameters (see legend below).

Legend:

1: Raw water apparent colour (in PtCo)
2: Raw water turbidity (in NTU)
3: Raw water pumped (in m^3/d)
4: Final water produced (in m^3/d)
5: Service water (in m^3/d)
6: Alum or ACH use (in kg/d)
7: Chlorine use (in kg/d)

Green	Daily data available (no limitations)
Orange	Daily data incomplete, with gaps or fragmented (limitations)
Yellow	Daily data was calculated by NWSC staff based on assumptions
Blue	Daily data can be calculated by the author based on assumptions
Grey	No daily data available

During digitisation, several peculiarities within the hard copy data became apparent. As Table 3 illustrates, the data series for most parameters are subject to substantial data gaps, including several months with missing data (panels indicated in grey) or fragmented data (panels indicated in red). Data gaps occur with durations of individual days up to several weeks or months. It was rarely possible to determine reasons for these interruptions. In addition, unexpected, unintuitive, or unrealistic values occur regularly that required closer examination and evaluation. Furthermore, several values were illegible and could not be properly determined. Other particularities, either for single DWTPs or individual record books, were observed as well. These include long-term assumptions by NWSC staff as well as changes in the data generation methodology, which were both not provided with unambiguous notes. Overall, the peculiarities resulted in several open questions and individual challenges during digitisation. The procedure of addressing them and thereby preparing the data is described in detail in Appendix B. In principle, the data preparation included filtering of data, error corrections, additional calculations, and making expert-based assumptions. All modified, adjusted, deleted, and assumed values, as well as all general assumptions, are marked in colour and/or provided with comments in the author's Excel file. Table 3 indicates months during which systematic, long-term assumptions were either recognised in the hard copy data as applied by NWSC (panels indicated in yellow) or were applied by the author (panels indicated in blue).

<u>Calculation of additional parameters</u>

After completing the digitisation and preparation of data, three additional parameters were calculated for each day with sufficient data availability. The additional parameters are coagulant dose rate, coagulant to turbidity ratio, and chlorine dose rate.

Coagulant dose rate was included to relate coagulant chemical quantities applied at the case study DWTPs to the water volumes processed at the plants. The evaluation of this parameter allowed to assess the intensity with which coagulant chemicals were added to the raw water at the plants and facilitated the comparability between the plants. It was calculated by dividing daily coagulant use by the corresponding raw water volume, as shown in Equation (6).

$$Coagulant\ dose\ rate\ \left(\frac{mg}{L}\right) = \frac{Coagulant\ use\ \left(\frac{kg}{d}\right)}{Raw\ water\ pumped\ \left(\frac{m^3}{d}\right)} \times 1{,}000\ \left(\frac{\frac{mg}{kg}}{\frac{L}{m^3}}\right) \qquad (6)$$

To put the coagulant dose rate just calculated in relation to the intake water quality at the case study DWTPs, the theoretical coagulant to turbidity ratio[5] was determined. For this, the parameter raw water turbidity was selected to represent intake water quality. It is a suitable measure for sediment and particle contents in water (see Chapter 2.2.2) and shows better data availability in the quantitative data base compared to apparent colour (see Table 3). The evaluation of the ratio allowed to better relate coagulant dose rates applied at the case study DWTPs to the respective raw water quality conditions. Thereby, statements on consistency and accuracy of coagulant dosing could be derived. The parameter was calculated by dividing the daily coagulant dose rate by the corresponding raw water turbidity, as shown in Equation (7):

$$Coagulant\ to\ turbidity\ ratio\ \left(\frac{mg}{L \times NTU}\right) =$$

$$\frac{Coagulant\ use\ \left(\frac{kg}{d}\right)}{Raw\ water\ pumped\ \left(\frac{m^3}{d}\right) \times Raw\ water\ turbidity\ (NTU)} \times 1{,}000\ \left(\frac{\frac{mg}{kg}}{\frac{L}{m^3}}\right) \qquad (7)$$

The case study DWTPs work with different coagulant chemicals. Alum is applied at the DWTPs of Lirima and Sono and ACH at the DWTP of Malaba-Tororo. To allow for a better comparison of coagulant-related parameters between the case study DWTPs, the values for Malaba-Tororo were provided in the form of theoretical alum equivalent (alum eq.) values as well. To estimate alum eq. quantities based on ACH quantities, the ACH values were divided by a conversion factor of 0.33 that was determined from the literature (Chew et al. 2016, p. 3157; Gebbie 2005, p. 77, 2006, p. 16). More details can be found in Chapter 2.3.2. Since a range of potential conversion factors is available in the literature, the selected conversion factor might lead to an over- or underestimation of the alum eq. quantities at Malaba-Tororo. However, as only an estimate should be given, the extent of this error was not investigated further.

As third additional parameter, chlorine dose rate was included to relate disinfectant quantities applied at the case study DWTPs to the water volumes processed at the plants.

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[5] Hurst et al. 2017 referred to this theoretical parameter as coagulant to influent turbidity ratio (pC*) or as coagulant to turbidity ratio (in mg/L alum/NTU). In this thesis, the latter designation was used.

The evaluation of this parameter allowed for a better comparison of the intensity with which disinfectant chemicals were added to the final water at the plants. It was calculated by dividing daily disinfectant use by the corresponding final water volume, as shown in Equation (8). However, as it was determined that the application of disinfectant chemicals was not affected by varying raw water qualities at the case study DWTPs, the disinfectant-related parameters were not considered in further evaluations of this thesis.

$$Chlorine\ dose\ rate\ \left(\frac{mg}{L}\right) = \frac{Chlorine\ use\left(\frac{kg}{d}\right)}{Final\ water\ produced\left(\frac{m^3}{d}\right)} * 1{,}000\ \left(\frac{\frac{mg}{kg}}{\frac{L}{m^3}}\right) \tag{8}$$

<u>Statistical evaluations</u>

Different monthly, annual, and overall statistical parameters (e.g., sum, mean, median, minimum, and maximum values) were determined for the selected and calculated parameters mentioned before. In this context, it is important to note that due to the varying data availability illustrated in Table 3, the yearly and overall statistical evaluations are not directly comparable between the plants as they include a varying number of data points from different points in time.

To be able to better compare the case study DWTPs with each other, bar chart diagrams for each selected and calculated parameter were created that present a selection of statistical parameters. Each bar chart diagram graphically illustrates overall mean values and standard deviations (SD) of uncertainty, and provide numbers for the mean, SD, minimum, maximum, median, and total number of observations. To bring these statistical parameters into a seasonal context, the same was created for the dry season (by including only values from December to February), and for the wet season (by including only values from March to November). Thereby, each bar chart diagram presents statistical evaluations from a total of nine data series for each parameter, namely for each of the three case study DWTPs during each of the three seasonal evaluations.

Furthermore, box plot diagrams for each parameter were created. Both the bar chart diagrams and the box plot diagrams for each parameter are presented and discussed in Chapter 4.2.

<u>Time series diagrams</u>

To provide an overview of the daily data over time, the selected and calculated parameters were graphically visualised in time series diagrams. For some parameters (i.e., raw water turbidity, coagulant use, and coagulant to turbidity ratio), the time series diagrams are presented and discussed in Chapter 4.2.

To allow for a better overview of the temporal course of parameters and to potentially compensate for random errors and outliers which are present in the daily data, also monthly time series diagrams were created and visualised. From these diagrams, it became clear that the data gaps in most daily data series, as discussed before with reference to Table 3, were reflected in the monthly values derived from them as well. For several parameters, this led to fragmented time series diagrams with low informative value. To fill those gaps, the existing monthly time series calculated based on daily data were combined with data provided by NWSC in monthly resolution, i.e., data from the quarterly and monthly reporting for the Eastern Region (see Table 2, record categories viii and ix).

In the process of combining the two data sources, several peculiarities within the quarterly and monthly reporting for the Eastern Region became apparent. These include contradictions and irregularities within each Excel file (e.g., values for a specific parameter that are provided in different table tabs parallelly differ from each other), as well as between the Excel files (e.g., individual values or value patterns are repeated from one month to one or more of the following months). These observations are most likely due to transfer errors caused by digital copying of individual values or the whole Excel template. To address the peculiarities, the monthly data series were further prepared in order not to consider false or mistakenly repeated values. The data preparation included filtering of data and assumptions made by the author and is described in detail in Appendix B, subsection “Monthly values”. By combining data from the two sources, it was possible to derive more extensive monthly data series. Based on these, time series diagrams for each of the selected and calculated parameters were created and are presented in Chapter 4.2. For the precipitation in the relevant upstream areas of the case study DWTPs, an additional monthly time series diagram is presented that shows the monthly values from the observation period in relation to the long-term monthly means. The diagram was created by Herrnegger (2020) and only modified by the author.

3.4.3. Simple regression analyses

To examine interconnections between the selected parameters, a variety of simple regression analyses were performed for the empirical relationships identified in the conceptual framework (see Figure 7). For each relationship, the following parameters were assigned for investigation, respectively:

- Relationship “Sources & mobilising factors → Water quality”: Examined based on precipitation and raw water turbidity,
- Relationship “Water quality → Treatment effort”: Examined based on raw water turbidity and coagulant use, as well as raw water turbidity and coagulant dose rate, and
- Relationship “Sources & mobilising factors → Treatment effort”: Examined based on precipitation and coagulant use, as well as precipitation and coagulant dose rate.

To get a first overview of these relationships, selected monthly time series (see Chapter 3.4.2, subsection “Time series diagrams”) were merged and displayed jointly. The combinations of parameters include precipitation and raw water turbidity, precipitation and coagulant dose rate, as well as raw water turbidity and coagulant dose rate. The combined time series diagrams are presented and discussed in Chapter 4.3.

In a subsequent step, the relationships listed above were investigated for their correlation at different temporal resolutions. Besides the daily and monthly data series obtained according to the procedure described in Chapter 3.4.2, also weekly mean and sum values were evaluated. These were calculated based on the daily data series for each parameter and each calendar week within the observation period. For the three temporal resolutions, the coefficients of determination (R^2) for the linear and, where applicable, natural logarithmic functional relationships between the selected parameters were determined. Detailed information on the statistical parameter R^2 are provided in Kutner et al. (2005, pp. 74–76). Logarithmic functional relationships are only applicable if the data series of the independent variable does not include any zero values. Within the examined data series, zero values were present in the precipitation data, for which only linear functional relationships could be considered. Self-evidently, only those data pairs could be included in the simple regression analysis for which both parameters involved were available for the same point in time. For each relationship and temporal resolution, R^2 was calculated for both the full data series, and for the data series after outlier analysis. The results are presented in a table and discussed in Chapter 4.3. For each evaluation, the table also indicates the number of observations considered in the respective calculation.

Furthermore, the relationships listed above were visualised in scatterplot diagrams indicating the regression curve, its functional equation, and the corresponding R^2 value. A selection of scatterplot diagrams for different temporal resolutions is presented and discussed in Chapter 4.3. Based on the R^2 table and the scatterplot diagrams, the extent to which precipitation, raw water quality, and treatment effort are correlated at the case study DWTPs is discussed in Chapter 4.3 to address research question III.

3.4.4. Multiple regression modelling approach

General overview

To estimate the response in treatment effort at the case study DWTPs to varying raw water quality and other environmental factors, a multiple regression modelling approach was developed based on the available data series. For this, suitable parameter(s) to represent variable treatment effort were determined as dependent variable(s) and associated influencing parameters as independent variables. As illustrated in the conceptual framework (see Figure 7), variable treatment effort is generally represented in this thesis by coagulant chemical use, disinfectant chemical use, backwash water volume, and energy consumption. Raw water quality is represented by raw water apparent colour and raw water turbidity. Environmental factors are represented by two precipitation related parameters. In addition, several control variables are conceivable. For the selection of suitable parameters from these candidates, the results from the activities described so far, background knowledge from the literature (see Chapter 2.4), as well as the data availability and reliability were considered. Furthermore, a scatterplot matrix was created according to the procedure described in GeeksforGeeks (2020) to illustrate potential correlations and collinearity between the parameters considered in this thesis. Finally, the temporal resolution of input data, as well as the estimator that should be used in the subsequent calculation, were determined. The considerations culminated in two regression equations, i.e., one to apply the multiple regression modelling approach to a single DWTP, and another to include all case study DWTPs in one equation. The regression equations, as well as the expected modelling results, are presented in Chapter 4.4.

Dependent variable(s)

As described in Chapter 3.4.2 in subsection “Selection of relevant parameters”, it was determined that parameter (7), disinfectant chemical use, is not affected by varying raw water qualities, which goes in line with findings from the literature (see Chapter 2.2.1). Therefore, the parameter was not considered as a variable to represent the response in treatment effort to varying raw water quality at the case study DWTPs. Regarding parameter (8), energy consumption, the quantitative data base provided by NWSC was too limited to make reliable statements on the relationship between raw water quality and treatment effort. Therefore, also energy consumption was not considered as a response variable in the multiple regression modelling approach.

According to Chapter 2.6, backwash water volumes were evaluated in this thesis as a potential surrogate for energy consumption in case the energy data availability would not be sufficient for all case study DWTPs. However, the quantitative data base of this thesis included no individual data series on backwash water volumes, but for an aggregated parameter called service water volume (see Chapter 4.2.3). Besides the backwashing of sand filters, this parameter additionally contains water consumption for flushing of sanitation facilities, cleaning of yards, and laboratory uses. It can further be assumed that it includes water consumption for watering the lawns at the DWTPs as well. Therefore, it was not possible to determine separate backwash water volume data series for the case study DWTPs from the available data. Although service water volume could have been used as a proxy, limited data availability and the absence of any data for the DWTP of Sono would have impeded comparability between the case study DWTPs if this parameter was included as a response variable in the modelling approach. Furthermore, the time series diagram for service water volume (see Figure 30) shows comparatively stable curves with long-term downward trends, while no distinct seasonal variations in response to varying raw water quality can be observed. This is underlined by Figure 26, which indicates similar mean service water values in the dry and wet season.

Therefore, it was assumed that the operational management at the case study DWTPs does not significantly adjust backwash water volumes to react to varying raw water qualities. This notion is partly confirmed by the literature. While some authors pointed to a clear correlation between raw water quality and backwash water volumes (Clark et al. 1985, p. 92; Singh and Mishra 2014, p. 74; Sthiannopkao et al. 2007, p. 710), Moore and McCarl (1987, p. 44) described the filtration stage as only a minor cost item within water treatment. This was underlined by Heberling et al. (2015, pp. 8744–8745), who reported that the backwash water pumps at a case study DWTP consumed only a "relatively minimal" amount of energy in comparison to the raw and finished water pumps. Moreover, Moore and McCarl (1987, p. 44) stated that the filtration stage at DWTPs is required anyhow to remove bacteria, algae, and other residues, regardless of the raw water turbidity levels. This implies that backwash water volume is not exclusively related to sediment load and particles in the processed water, which decouples the parameter from raw water turbidity to a certain degree. Against this background, it appears reasonable to exclude backwash water as a response variable in this thesis.

In contrast to the parameters discussed before, coagulant chemical use appears suitable to represent the response of treatment effort to varying raw water qualities. As shown in Figure 31, the parameter was largely available within the quantitative data base, including 360, 474, and 1,122 daily observations for Lirima, Sono, and Malaba-Tororo, respectively. The applied chemical quantities varied with time and seasonality, implying a response to varying raw water qualities (see Figure 31, Figure 33, and Figure 34). The simple regression analyses for the relationship “Raw water turbidity → Coagulant use” show that the parameters are correlated (see Table 5), including values of up to R^2 = 0.63 (linear form) and R^2 = 0.71 (logarithmic form) for the weekly resolution at Malaba-Tororo. These findings delivered a reasonable basis to include coagulant chemical use as a parameter to represent the response of treatment effort to varying raw water quality at the case study DWTPs. This concept is widely confirmed and extensively used by the literature, as discussed in Chapter 2.4.3. Hence, the parameter was determined as the dependent variable in the multiple regression modelling approach presented in Chapter 4.4, where it is abbreviated by $Coag_t$.

Independent variable to represent water quality

Both raw water quality parameters analysed in the present thesis, namely apparent colour and turbidity, are related to sediments and particles in water and correlate with each other (Crittenden et al. 2012, p. 41). For the relationship “Raw water apparent colour → Raw water turbidity”, comparatively high R^2 values of up to 0.85 were determined from the quantitative data base (linear form, weekly resolution, Malaba-Tororo). While both parameters are principally suited to represent stream water quality variations at the intakes of the case study DWTPs, it was therefore decided to opt for only one of the two to avoid collinearity in the multiple regression model. In fact, when including both parameters, the variance inflation factors (VIFs) were determined to $VIF_{turbidty}$ = 2.55 and VIF_{colour} = 3.35 for the weekly data series at Malaba-Tororo. According to Johnston et al. (2018, p. 1958), however, VIFs below 2.5 are desirable to rule out considerable collinearity within the multiple regression analysis.

From the two parameters, turbidity was selected to represent raw water quality in the multiple regression modelling approach. As illustrated in Table 3 and Chapter 4.2.2, the parameter shows considerably better data availability within the quantitative data base compared to apparent colour. While only 3 and 30 daily apparent colour observations are available for Lirima and Sono, respectively, the numbers for turbidity are at 303 and 258 (see Figure 17 and Figure 18). Furthermore, findings from the literature plead for turbidity rather than for apparent colour. Westling et al. (2020, p. 4) described turbidity as a commonly used water quality indicator for the presence of sediments, suspended clay, silt, finely divided organic matter, algae and other microorganisms. Singh and Mishra (2014, p. 74) referred to the parameter as a reasonably accurate measure of the overall raw water quality. From the 24 studies evaluated in the review by Price and

Heberling (2018), 12 used raw water turbidity as a water quality measure, while none used a colour related parameter. The authors found that water-quality elasticities based on turbidity appeared to be the most robust, since they were consistent despite the diverse data and analytical methods applied in the reviewed studies.

In summary, raw water turbidity was subject to better data availability in the quantitative data base compared to apparent colour and allowed for a comparison of the results with the literature. Hence, the parameter was selected as an independent variable for the multiple regression modelling approach presented in Chapter 4.4, where it is abbreviated by $Turb_t$. After removing apparent colour, the VIF for turbidity of the weekly data series at Malaba-Tororo declined to $VIF_{turb} = 1.18$, while the VIFs of all selected control variables were below 2.5 as well. Thereby, the requirements formulated by Johnston et al. (2018, p. 1958) regarding the VIFs were fulfilled.

Control variables

Most studies considered in the review article by Price and Heberling (2018, p. 198) included control variables to account for factors that may bias parameters of interest. Among the evaluated modelling approaches, the authors found control variables regarding processed water volumes, weather conditions, source water type, system properties, and service population characteristics. In the multiple regression modelling approach of the present thesis, a total of three control variables will be included, as elaborated in the following.

First, a control variable regarding the water volumes processed at the case study DWTPs should be included. It was assumed by the author that in general, higher volumes of processed water lead to increased use of coagulant chemicals, and vice versa. Thereby, the coagulant dose rate, which is crucial for the removal of sediments and particles from the raw water, is kept steady in case of constant raw water qualities. In case raw water quality varies, coagulant dose rates are adjusted, which implies adjustment of the coagulant use but not necessarily of the processed water volumes. In contrast, in case the processed water volumes vary, coagulant use is adjusted even if raw water quality is constant. As a result, it seemed imperative to include a control variable for processed water volume to allow separating changes in coagulant use due to varying water volumes from those generated by varying raw water quality. The literature largely supports including a control variable for processed water volume in relevant modelling approaches, as discussed in Chapter 2.4.3. In their review article, Price and Heberling (2018, p. 198) indicated that processed water volume was the most common control variable among the reviewed studies, contained in 16 of 24 reviewed modelling approaches. According to the authors, the control variable is consistent with economic theory. For example, Singh and Mishra (2014, p. 78) included the variable as it allows to account for scale effects.

The quantitative data base provided by NWSC included both (3) raw water pumped and (4) final water produced as variables related to processed water volumes. Both parameters are highly correlated to one another, with R^2 values of up to 0.96 and 1.00 for the relationship “Raw water pumped → Final water produced” (linear form) for the weekly resolution at Lirima and Sono, respectively. The causal correlation of the two parameters due to their direct connection within the water treatment train was further strengthened in this thesis since the respective data series were partly calculated from each other using a conversion factor, as described in Appendix B. Therefore, it was decided to select only one of the two parameters for the multiple regression modelling approach to avoid collinearity, i.e., to avoid VIFs above 2.5. As shown in the schematic flow diagrams of the case study DWTPs in Figure 10, Figure 11, and Figure 12, coagulant chemicals are applied to the processed water stream shortly after inflow or pumping into the respective DWTP. As coagulant chemical use was selected earlier as the response variable to represent treatment effort, it appeared useful to include raw water pumped as a control variable in the modelling approach. In the multiple regression equations presented in Chapter 4.4, raw water pumped is abbreviated by Rwp_t.

As second control variable, precipitation was included in the multiple regression modelling approach. As discussed in Chapter 2.2.3, both rainfall intensity and volume are important environmental factors for the mobilisation of sediments and particles in catchments, which are then transported and delivered to streams mainly by surface flow. Further on, the constituents end up at the intakes of DWTPs, where they affect raw water turbidity and hence water treatment. However, the described interconnection between precipitation and treatment effort is already largely covered by the independent variable raw water turbidity described above. Beyond this relationship, the operational management at the case study DWTPs indicates that coagulant dose rates are partially adjusted exclusively based on observed precipitation. As described in Chapter 4.1, jar test experiments to determine optimum coagulant dose rates before their application are only performed at Malaba-Tororo. According to the respective plant overseers, dosing decisions at Lirima and Sono are mainly made based their professional experience under consideration of the weather conditions. They further explained that rainfall in the areas of Lirima and Sono leads to a direct increase of alum dosing at the respective DWTP, i.e., without any time delay, and before jar test experiments are performed. It fits in with this that the simple regression analyses presented in Chapter 4.3 show a weaker correlation between precipitation and raw water turbidity compared to its correlation with coagulant use. For example, R^2 values of up to 0.13 for the relationship "Precipitation → Raw water turbidity" (linear form, weekly resolution, Malaba-Tororo, without outlier analysis) were observed, while under the same boundary conditions, a R^2 value of 0.26 was observed for the relationship "Precipitation → Coagulant use". Based on these findings, it seems reasonable to assume a direct causal link between precipitation and coagulant use at the case study DWTPs, at least at Lirima and Sono, that should be addressed in the present modelling approach. In the multiple regression equations presented in Chapter 4.4, precipitation is abbreviated by $Rain_t$.

Considering precipitation as a control variable is only partly done in the literature, as described in Chapter 2.4.3. Price and Heberling (2018, p. 196) pointed out that control variables with regards to weather conditions were only included by some of the reviewed studies, e.g., by Dearmont et al. (1998) and Vincent et al. (2016). Like the present study, Dearmont et al. (1998, p. 851) included both rainfall and raw water turbidity in their modelling approach and argued that water treatment expenditures may be affected by both runoff and sediment levels. Their estimation results indicated that the rainfall variable was statistically significant at the 5 % level. Vincent et al. (2016, p. 63) included both land use and rainfall as environmental inputs in their model. The authors stated that controlling for rainfall was important to reduce the risk of biased estimation of the effect of land use on treatment costs. Westling et al. (2020) included both a water quality index and precipitation (i.e., the average annual rainfall in the area closest to the respective DWTP) as independent variables in their chemical cost function. The authors argued that rainfall was an important control variable as it increases the runoff of pollutants into waterways. The results of Westling et al. (2020, p. 7) indicated that the variables associated with turbidity and precipitation were both significant ($p < 0.05$). Other authors included precipitation in their multivariate models as well, but with an indirect influence on treatment expenditures. An example is the study by Singh and Mishra (2014, p. 78) who included the monthly average weighted rainfall as an independent variable in their forest cover-turbidity equation. The results from the equation were then linked to the turbidity-treatment cost relationship in a recursive fashion. A different approach was taken by Forster et al. (1987, p. 350), who stated that rainfall intensity affects water treatment expenditures due to its effect on erosion. However, in their model, the authors substituted turbidity for rainfall, soil moisture, and season of the year. Thereby, rainfall was not included as a stand-alone variable. Price and Heberling (2018, p. 198), with reference to Holmes (1988, p. 362) and Vincent et al. (2016, p. 64), mentioned that precipitation may not only lead to deteriorated water quality via increased runoff, but also to a dilution effect that reduces contaminant concentrations at the water intake of a DWTP. Price and Heberling (2018, p. 198) concluded that the overall effect of increased precipitation can be ambiguous, depending on the importance of the runoff relative to this dilution effect.

Forster et al. (1987, p. 350) mentioned that besides precipitation, also season of the year and soil moisture affect the treatment effort at a DWTP. Dearmont et al. (1998) and Sthiannopkao et al. (2007) showed that treatment efforts are higher during wetter periods. Among the studies reviewed by Price and Heberling (2018, p. 196), Abdul-Rahim and Mohd-Shahwahid (2011) and Heberling et al. (2015) included explanatory variables related to the seasonality in their modelling approaches. Abdul-Rahim and Mohd-Shahwahid (2011) argued that water treatment costs might be affected by increased runoff and sediment levels in the wet season compared to the dry season. Hence, the authors included a 0-1 dummy variable (dv) as independent variable, where 1 represents the wet season, and 0 represents the dry season. However, their multiple regression analysis showed that the regression coefficient for the dv was statistically insignificant. Heberling et al. (2015, p. 8748) included a dv to represent seasonality in terms of spring and summer months in their modelling approach. The authors argued that coagulant dosing at their case study DWTP occurs stepwise and is based not only on water quality, but also on seasonal triggers (Heberling et al. 2015, p. 8751). In their analysis, the dv for seasonality was statistically significant ($p < 0.01$), indicating that spring and summer months resulted in higher treatment efforts (Heberling et al. 2015, p. 8750).

Based on the results by Heberling et al. (2015), seasonality should be included as a third control variable in the present thesis. Particularly the clear shifts between dry and wet season in the SMMRB, associated with distinct seasonal differences observed for many parameters discussed in Chapter 4.2, motivated this approach. It was assumed by the author that the seasonality in the SMMRB has major impacts on land cover (e.g., vegetation, agricultural activities), soil moisture conditions, landslides, and failures. This may influence the mobilisation of sediments and particles and their delivery into streams, even regardless of the precipitation sum during the respective observation. Furthermore, seasonal differences in terms of varying frequencies, durations, and intensities of precipitation may systematically influence coagulant dosing decisions at the case study DWTPs. This is expected particularly at Lirima and Sono, where coagulant doses are determined based on professional experience of the plant overseers considering the weather conditions.

To include the seasonality in the present multiple regression modelling approach, the use of dummy variables as Abdul-Rahim and Mohd-Shahwahid (2011) and Heberling et al. (2015) proposed seemed not ideal. Both authors included dummies to represent the wet season or summer months (e.g., March, April, and May), or the absence of those. However, during the observation period, considerable precipitation variabilities were observed in the SMMRB, as the seasonal rainfall patterns showed distinct deviations between September 2016 and January 2020 (see Figure 16). Assigning certain dummy values to specific months, e.g., March to November, would hide these effects. In order to circumvent this problem, the sum of precipitation in 14 days prior to the respective observation should be considered instead. This approach allowed to estimate antecedent soil moisture and humidity conditions in the river basin that result from hydro-meteorological conditions in the near past of an observation, without interfering with the precipitation of the current observation. Furthermore, this concept allowed to capture any lagged effects of precipitation on coagulant use, e.g., time lags due to delayed runoff processes. In the multiple regression equations presented in Chapter 4.4, the seasonality is abbreviated by $Season_t$.

Besides these three control variables related to processed water volume, precipitation, and seasonality, no further were included in the multiple regression modelling approach of present thesis. From the propositions made by Price and Heberling (2018, p. 198), source water type and systems properties appeared not suitable since the case study DWTPs use the same source type (i.e., stream water), and apply the same principal treatment approach (i.e., conventional water treatment). Therefore, no effect would be observed by including a variable regarding these characteristics. Also, service population characteristics were excluded since information on these are limited for the SMMRB, and since only three water supply systems (i.e., three service populations) were considered which would not add much to the modelling approach.

Dummy variables

To be able to consider all case study DWTPs in the multiple regression model, the equation established so far was expanded by introducing two 0-1 dummy variables (dv) for Sono and Malaba-Tororo. Lirima was used as a reference and hence did not require a separate dv.

Temporal resolution of input data

Data in daily, weekly, and monthly temporal resolution were either provided with the quantitative data base or calculated by the author, as described in Chapter 3.4.2. While daily data has a higher degree of detail and culminates in a higher number of data points, weekly and monthly data smoothen out certain daily peaks and outliers. Thereby, an aggregation of data to longer time periods may show underlying proportional correlations which are not visible in the daily data. For the present multiple regression modelling approach, a balance between number of data points and reliability of the results was perceived as desirable. Therefore, weekly values were selected as input data resolution for the modelling approach.

As Price, Heberling (11/8/2017, p. 12) pointed out, water-quality elasticities are generally only relevant for small changes in water quality, which speaks for at least some kind of temporal aggregation to avoid extreme fluctuations within the data series. Though in the literature, most authors used monthly or even yearly values (see Chapter 2.4.3), the selection of weekly values seems appropriate as no publication makes any statements that are contrary to this approach. Furthermore, it is close to the approach by Abdul-Rahim and Mohd-Shahwahid (2011) who used two-weekly observations.

Graphical representation of collinearity

Based on the response variable, explanatory variables, and temporal resolution selected before, a scatterplot matrix was created as shown in Figure 9. For the sake of completeness, also parameters that were not selected as variables for the multiple regression model were included. The figure shows frequency histograms for each parameter, as well as scatterplots for any combination of parameters. Thereby, it allows to identify collinearity among the considered data series. The frequency histograms indicate a right skew in the data series of many parameters selected for the multiple regression model, which speaks for a linearisation as discussed below. Highlighted in red boxes are the relationships that are considered in the multiple regression modelling approach presented in Chapter 4.4.

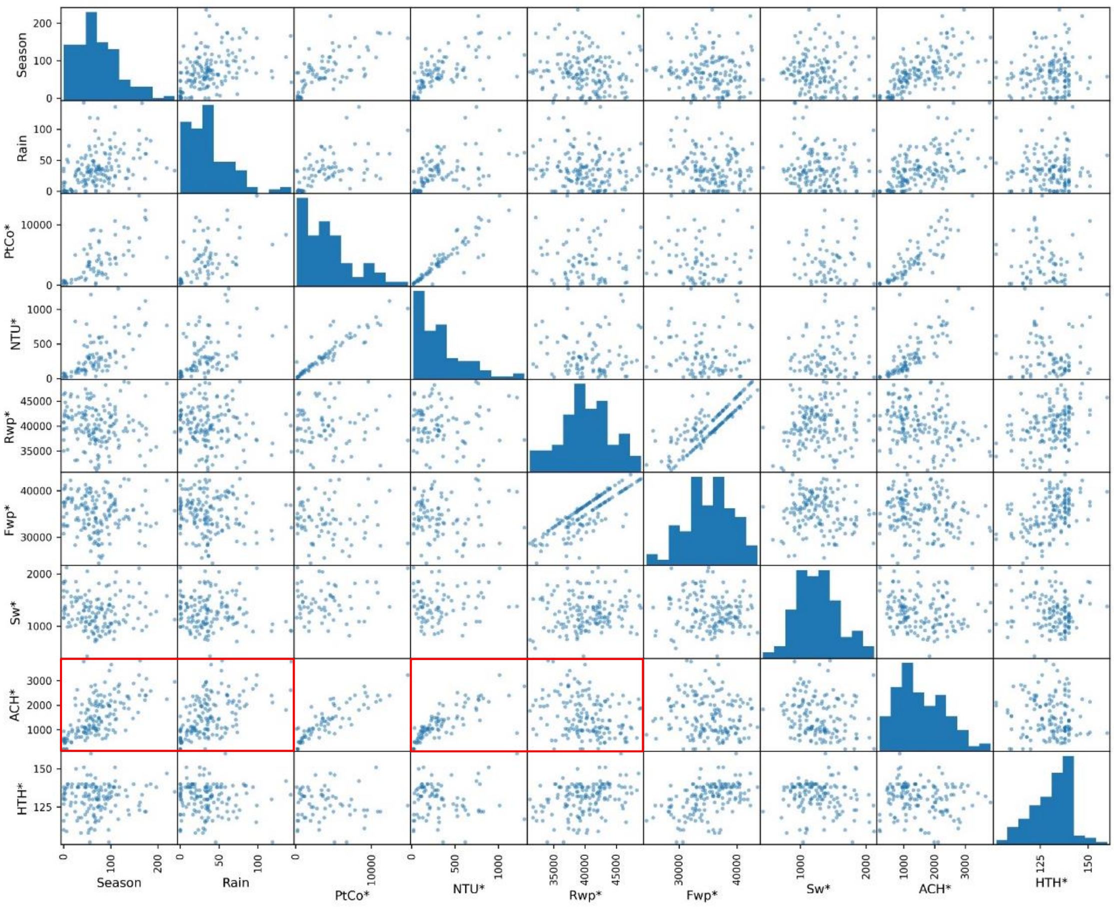


Figure 9: Scatterplot matrix of all parameters considered for the multiple regression model, based on weekly values. An asterisk (*) indicates that the data series were included after outlier analysis. The main diagonals contain frequency histograms for each parameter. Indicated in red are the correlations included in the multiple regression model presented below. Abbreviations: Season = seasonality (precipitation sum in previous 2 weeks), Rain = rainfall (precipitation sum in current week); PtCo* = raw water apparent colour; NTU* = raw water turbidity; Rwp* = raw water pumped; Fwp* = final water produced; Sw* = service water; ACH* = ACH use; HTH* = chlorine High Test Hypochlorite (HTH) use.

Data transformation

According to Price and Heberling (2018, p. 199), a functional form must be defined for the statistical estimation of a model that represents the data generating process. In their review article, the authors indicated that the log-linear form is used most frequently among the evaluated studies due to its ability to capture nonlinearity and ease of interpretation. Singh and Mishra (2014, pp. 78–79) argued that a non-linear relationship between source water quality and treatment effort is reasonable for the water treatment industry, since expenditures on chemicals and other operating inputs first increase rapidly with turbidity, and then level off as a certain saturation index is reached. Moreover, the authors stressed that the log-linear form allows to better approximate a normal distribution. This appeared advisable for the present thesis as well, since the frequency histograms in Figure 9 indicate a right skew in the data series of most parameters considered for the multiple regression modelling approach.

Based on these insights, the log-linear form was selected for the present thesis as well. To implement this, all parameters in the multiple regression modelling approach, except for the dummy variables, were linearised by transformation into their natural logarithmic form. The log-linear form allowed to directly determine water-quality elasticities based on the modelling results without any further calculation (Warziniack et al. 2017, p. 14).

Applied estimator

In their review article, Price and Heberling (2018, p. 199) indicated that the Ordinary Least Squares (OLS) estimator was applied most frequently among all evaluated studies. Hence, this estimator will be used in the present thesis as well.

3.4.5. Multiple regression results and water-quality elasticities

Since the multiple regression model presented in Chapter 4.4 includes a log-linear transformation, zero values within the input data series cannot be considered. If this issue was not addressed, potentially important information from the dry season with 0 mm precipitation per observation would be lost for the estimation. Hence, for any data series that included zero values (i.e., precipitation, seasonality), each observation was increased by +0.00001 mm. This allowed to also consider data tuples that formerly included zero values in one or more of their data series.

As the multiple regression analyses should be carried out using OLS, the data series were examined to make sure they met the requirements of the estimator, i.e., that they fulfilled the assumptions of the Gauss-Markov theorem. This examination of the data series is documented in the author's Excel file, including the test for heteroscedasticity, and calculation of the VIFs for all input data series. Since all tests were successful, it could be confirmed that the data series met the requirements for multiple regression analyses using the OLS estimator.

Based on both equations presented in Chapter 4.4, the multiple regression model was run using all available weekly data tuples for the selected variables, including outliers. First, Equation (10) was estimated for Malaba-Tororo alone. Since the DWTP showed the most stable operations during the observation period, the best data availability and reliability, and the most accurate coagulant dosing procedure of the case study DWTPs, results of this estimation promised greater accuracy compared to the subsequent evaluation. Thereby, the impact of turbidity variations on chemical treatment effort was estimated for a water supply system located downstream within the SMMRB. Then, Equation (11) was estimated considering the available data from all case study DWTPs. For this evaluation, the dependent variable ACH use at Malaba-Tororo had to be converted into alum equivalent use by applying a conversion factor of 0.33 to each observation (see Chapter 3.4.2, subsection "Calculation of additional parameters"). The analysis allowed for a comparison of the three plants, though limited data availability and reliability decreased the informative value to a certain extent. The results from both estimations, i.e., the intercept, individual regression coefficients β_i, as well as corresponding statistical indicators, are provided in a table and discussed in Chapter 4.5.

Due to the log-linear transformation applied to the multiple regression model, the regression coefficients can be interpreted as elasticities, i.e., the percent change of the dependent variable resulting from a 1 % change in the respective independent variable (Warziniack et al. 2017, p. 14). Consequently, the regression coefficients of the water quality parameter turbidity (β_{WQ}) are the water-quality elasticities of treatment effort. Based on Price, Heberling (11/8/2017, p. 12) and Price and Heberling (2018, p. 195), they are defined as the percentage change in water treatment effort resulting from a 1% change in source water quality, thereby expressing the responsiveness of treatment effort to changes in source water quality. Applied to the present study, the concept can be illustrated with the following formula (after Price, Heberling (11/8/2017, p. 12)):

$$Turbidity\ elasticity\ \mu = \frac{\Delta\ Chemical\ treatment\ effort\ (\%)}{\Delta\ Source\ water\ turbidity\ (\%)} \qquad (9)$$

The water-quality elasticities derived from the multiple regression analyses are presented and their implications are discussed in Chapter 4.5.

3.5. Uncertainties of the study

In general, the quantitative data provided by NWSC includes both systematic and random errors. Furthermore, the absence of complete and consistent data series resulted in several assumptions made either by NWSC staff or by the author, as described in Appendix B. Consequently, the results and calculated figures are prone to errors and deviations as well as systematic under- or overestimations. Various sources of error could be identified by the author during collection, preparation, and analysis of the quantitative data base, as described in the following. In addition, it is likely that further sources of error exist that influenced the analysis results but did not become visible while working on this thesis.

The following potential sources of error were identified:

- The quantitative data was generated, recorded, and compiled by different NWSC staff members in the last years as part of the in-house monitoring and evaluation.

The author was not present during these processes, i.e., during sampling, water quality measurements, determination of operating parameters, recording of the determined values, and compilation of record books. Therefore, the author cannot assure correct data generation. No calibration certificates for water quality test devices or water meters were provided; neither were guideline documents on internal processes, responsibilities, or quality control measures. To the knowledge of the author, the daily data was not checked for credibility and consistency, nor validated by any third party.

Though there are no evident indications for a general mistrust in the provided quantitative data, potential sources of error are numerous and include measurement errors due to wrong sampling, insufficient test equipment, imprecise analysis results, or missing calibrations of water quality test devices and water meters; documentation errors due to careless mistakes or transmission errors; or biased monitoring and evaluation due to economic constraints or mandatory water quality requirements. In summary, the author cannot assess the accuracy and error probability of the quantitative data and had to rely on the information provided by NWSC.

- Individual values or series of values sometimes appeared imprecise, unintuitive, or unrealistic. For example, raw water turbidity at Lirima DWTP was determined to be at precisely 40 NTU for twelve consecutive observations from 29th November to 10th December 2017. Alum dose rate at Sono DWTP was calculated to an unexpectedly high value of 4.762 kg/L on 28th July 2019. In several instances, values from individual days were repeated on subsequent day(s), e.g., raw water apparent colour and turbidity are both identical on 24th and 25th June 2017. Such values or series of values are unintuitive and potentially inaccurate. However, causes for such anomalies or whether there was an error associated with them were not further investigated by the author and are out of scope of this thesis.
- In case daily data for complete months exists, deviations between the monthly sum and mean values calculated by the author and those indicated in the record books were frequently observed. This may be due to calculation errors by the author or NWSC staff, or due to errors in the data series (i.e., monthly sum or mean values might be correct, but individual daily values might not). This inconsistency was not further investigated by the author.

- Missing raw or final water meter readings due to faulty measuring devices lead to assumptions made by either NWSC staff or by the author, as described in Appendix B. Missing daily water volumes were estimated based on other, existing values. For example, the raw water meter at Malaba-Tororo DWTP was faulty from 1st January 2018 to 30th November 2018. For the entire time, raw water values were calculated by NWSC staff based on measured daily final water values and a conversion factor of 1.149. A similar approach was adopted by the author in several cases. The time series created are no independent, stand-alone record series but depend on another data series including a systematic deviation. Such estimations and the underlying simplifying assumptions lead to systematic errors in the time series, which potentially create under- or overestimations of the respective water volumes over long time periods.

- The determination of daily water volumes by NWSC contained several contradictions and anomalies regarding the approaches for daily value creation and the assignment of calculated daily values to raw or final water (see Appendix B). These inconsistencies within time series lead to systematic errors, which potentially created under- or overestimations of the respective water volumes.

- During digitisation of the hard copies, it was not possible to unequivocally identify certain values, either due to cut-offs or blurring caused by photocopying, or due to illegible handwriting. Sometimes, commas were missing, or it was not clear where exactly the comma was set. Frequently, smaller assumptions had to be made by the author to digitise individual values and to avoid contradictions between values (see comments in the author's Excel file). In addition, the author may have made transferring errors while manually digitising the hard copy data to the author's Excel file. The digitised values were not validated by any other person.

- The Excel files from the monthly and quarterly reporting contained numerous contradictions, both in themselves (i.e., unambiguous values for a specific parameter, month, and DWTP were not equal in different table tabs), and between the Excel files (e.g., individual values or value patterns were repeated from one month to one or more of the following months). As described in Appendix B, an attempt was made not to consider false or mistakenly repeated values in order to avoid transfer errors. Yet, this procedure is associated with uncertainties. The correctness of the selection of monthly values that was made by the author cannot be validated.

Besides these uncertainties generated from the NWSC data, further potential sources of error exist with regards to the methodology and the precipitation data provided by Dr. Mathew Herrnegger. These include:

- To compare the treatment efforts at the case study DWTPS with each other, ACH quantities at Malaba-Tororo were converted into alum equivalent quantities with a conversion factor of 0.33. While this value was estimated based on existing literature, contradicting values can be found in the literature as well that differ clearly (e.g., Gebbie (2001, p. 44) indicates a conversion factor of only 0.2). The chosen conversion factor might lead to considerable overestimation of the alum equivalent use at Malaba-Tororo DWTP.

- The precipitation data may be subject to random errors and systematic under- or overestimations as well. The exploited Climate Hazards group InfraRed Precipitation with Stations (CHIRPS) dataset is built on interpolation techniques and high resolution, long record period precipitation estimates that in turn are based on infrared cold cloud duration observations. CHIRPS is a satellite precipitation product and although station data is included, there are uncertainties in the areal rainfall estimates. A comprehensive assessment of different satellite precipitation products for the SMMRB is provided by Omonge et al. (2021), who nevertheless showed a good agreement between CHIRPS and station observations for the study area. However, the author of this thesis cannot assess the accuracy and error probability of the precipitation values.

In conclusion, several (potential) sources of errors can be identified from the quantitative data base and the methodology, which may limit the informative value of the study. The extent of error was not assessed for this thesis. It is certain that the results and calculated figures presented in Chapter 4 do not precisely reflect reality at the SMMRB and the case study DWTPs. Due to a uniform methodological approach and consistent assumptions applied by the author, acceptable statements may nevertheless be made for the relation of the results with each other. Furthermore, reliable general statements and trends can be derived from the study.

4. Results and discussion

4.1. Comparison of the case study DWTPs

As many drinking water supply schemes in the SMMRB, Lirima, Sono, and Malaba-Tororo face several comparable challenges. According to Moses Butele, the main challenges are impaired raw water quality due to human activities as well as seasonal challenges associated with variability in precipitation.

The former is reflected in elevated levels of heavy metals, pesticides, and especially sediments and particles in streams in the SMMRB. According to Moses Butele, heavy metals and pesticides are not perceived as serious issues since they can be well removed by the treatment systems in the DWTPs. However, he reports that sediments and particles pose several challenges and threats to drinking water supplies in the river basin. For example, silt accumulations at the raw water intakes can block the intake pipes to the DWTPs. If sediments and particles are taken up with the raw water, they can damage raw water pumps and generate negative effects for specific treatment units, particularly for sedimentation, filtration, and coagulation. This occurs to a greater extent during the rainy seasons. While sedimentation tanks need to be drained and cleaned frequently (every three months in the dry season, every month in the rainy season), filters need regular backwashing to prevent a clogging effect. Both measures result in high internal water uses at the DWTPs. Furthermore, increased sediment and particle contents in raw water lead to increased use of coagulant chemicals, especially in the wet seasons.

As a cause for elevated sediment and particle loads in streams, Moses Butele emphasises human activities, particularly agricultural farming, and resulting soil erosion. Thereby, he identifies a direct link between agriculture and challenges to drinking water supply in the SMMRB. As an example, he mentions farming right up to the riverbanks including removal of natural vegetation along riparian areas of the streams, which previously served as buffer zones and natural water filters, and reduced flash floods. The food crops planted instead are not well suited to filter water and cannot prevent the inflow of sediments and particles into streams. Usually, there are no erosion prevention measures accompanying agricultural practices in the SMMRB. In addition to these aspects, John Ogire mentions a general population growth in the SMMRB, resulting in higher demands for resources as well as deforestation activities. In summary, human activities in the SMMRB increase soil erosion and result in surface water quality deterioration, particularly in the wet seasons.

The mentioned challenges vary between the seasons. In the dry season, reduced stream water volumes result in a competition for water between different consumers. According to Moses Butele, this results in insufficient water quantities left for drinking water supply and other uses. In the wet season, landslides, earth movements, and floods occur that can damage water supply pipes and treatment plant buildings. According to Moses Butele and Sara Mbabazi, Sono is particularly affected by such challenges. The resulting supply interruptions are confirmed by the quantitative data base for Sono. Besides damages to the plant in October 2018, which were covered by the media (Daily Monitor 2018; NTVNews 2018), John Ogire mentions land movements in May 2019 that affected the transmission lines. In contrast, he states that landslides and earth movements are no major issue at Malaba-Tororo, as the area was well surveyed and is characterised by flatter topography which is less prone to landslides. Besides these aspects, the wet season poses challenges to the DWTPs regarding a stable and reliable energy supply, which is reported to be particularly insufficient in the wet seasons. In recent years, climate variability in the SMMRB lead to an increase in the described challenges, as shifting patterns of dry and wet seasons and more frequent floods are observed for the river basin.

According to John Ogire, the case study DWTPs are all provided with the necessary equipment to perform various water quality measurements, including the determination of apparent colour and turbidity (photometers and turbidimeter tubes at all DWTPs; turbidimeter 2020 at Malaba-Tororo) (see Chapter 3.1). To give a first overview of raw and final water quality at Lirima, Sono and Malaba-Tororo DWTPs, Table 4 lists average results for several water quality parameters. Apparent colour and turbidity will be discussed in more detail in Chapter 4.2.2. According to Moses Butele, the two DWTPs located more upstream, Lirima and Sono, experienced no considerable changes in raw water quality in recent years. Here, fluctuations occur predominantly with the seasonality, including impaired raw water qualities during the wet season. In contrast, he reports that raw water quality at Malaba-Tororo has deteriorated in recent years, and that river levels increased in the wet seasons. This is confirmed by hydrometeorological analyses for the region showing that the period 2010-2020 was exceptionally wet compared to the long-term average of 1981-2020 (Herrnegger et al. 2021).

To address the raw water quality challenges described before and to produce a drinking water that conforms to the Ugandan National Standards for potable water, the case study DWTPs apply the same principal treatment approach. Figure 10, Figure 11, and Figure 12 show schematic flow diagrams of Lirima, Sono, and Malaba-Tororo, respectively. The applied conventional treatment is typical for DWTPs in the region that utilise stream water as raw water. As explained in Chapter 2.3, conventional treatment consists of a sequence of screening, coagulation, flocculation, sedimentation, sand filtration, disinfection, and subsequent distribution. At the time of the site visit to Sono, its sand filters were not operational, as indicated in Figure 11. To repair the system, a new backwash water pump would be required. Malaba-Tororo operates with two treatment lines in parallel, referred to as old line and new line.

Parameter \ DWTP	Lirima			Sono			Malaba-Tororo		
	Mean	SD	n	Mean	SD	n	Mean	SD	n
Raw water parameters									
pH (-)	7.72	0.27	6	7.90	0.41	8	7.59	0.55	14
Electric Conductivity (µS/cm)	80.64	20.67	8	87.40	17.54	8	145.08	35.70	14
TSS (mg/L)	5.75	6.73	8	3.14	1.86	7	461.25	759.81	12
Total alkalinity (mg/L as $CaCO_3$)	50.86	9.58	7	50.00	17.89	6	79.20	17.79	10
Total hardness (mg/L as $CaCO_3$)	58.57	29.11	8	74.00	33.11	6	70.00	10.81	11
Total iron (mg/L)	0.144	0.034	6	0.133	0.068	6	1.288	1.008	12
Faecal coliforms (CFU/100 mL)	19.50	29.77	4	12.50	9.88	4	1,412.42	1,523.08	12
Final water parameters									
Aluminium residual (mg/L)	0.15	0.08	6	0.30	0.20	5	0.05	0.05	9
Free residual chlorine (mg/L)	0.57	0.10	7	0.53	0.27	6	1.02	0.42	10
Total residual chlorine (mg/L)	ND	ND	0	ND	ND	0	0.89	0.63	2
E-coli (CFU/100 mL)	0	0	2	0	0	1	0	0	3

Table 4: Mean values, standard deviations (SD), and number of values (n) for different raw and final water quality parameters at the DWTPs of Lirima, Sono, and Malaba-Tororo. Values calculated based on data from the evaluation sheets on water quality (see Table 2, record category iii), after outlier analysis. The analyses were performed with one-off samples (one sampling day per month, i.e., no monthly mean values) in the central NWSC laboratory in Mbale town and confirmed by Peter Obol or Moses Butele. ND = not determined.

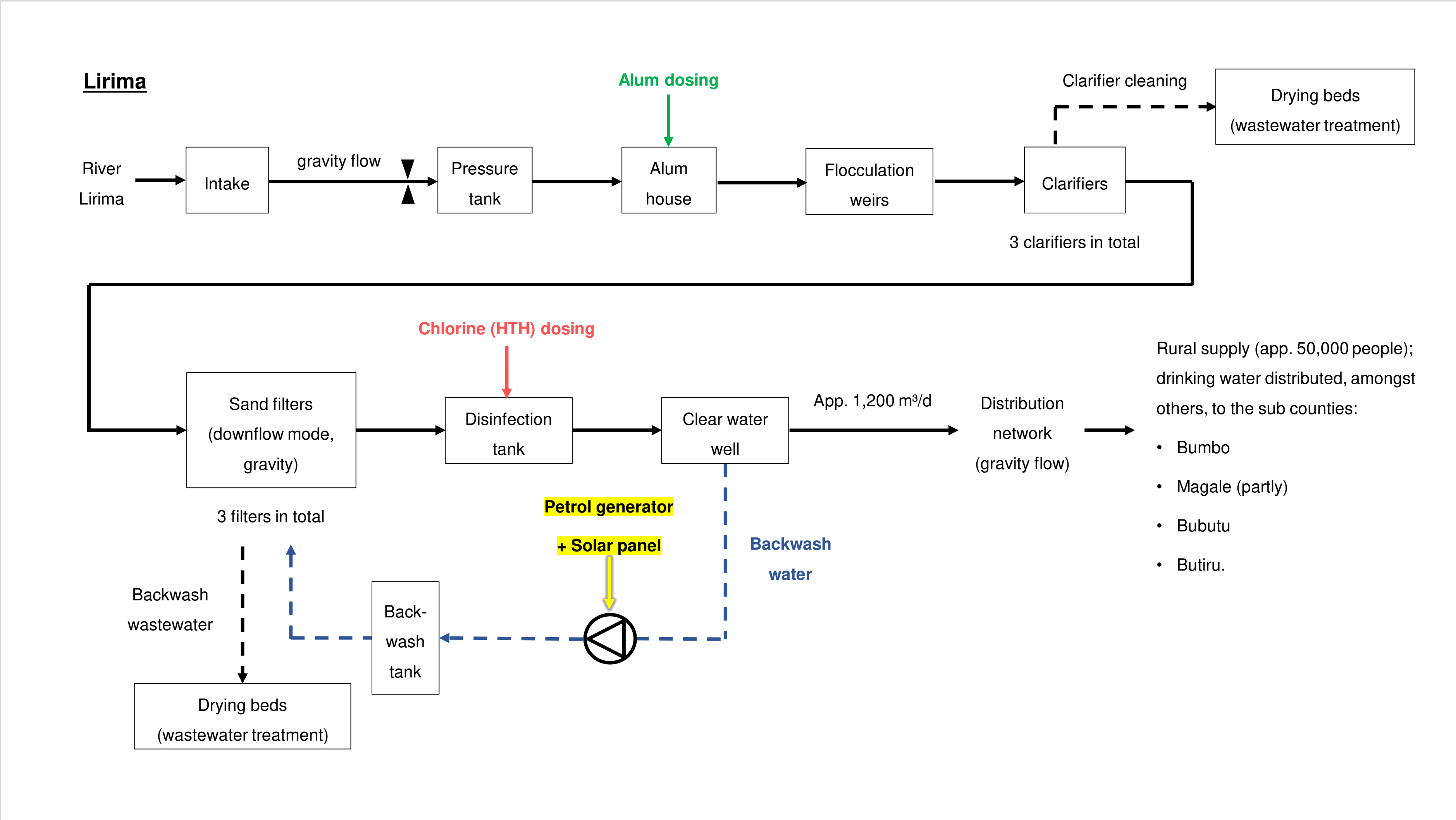


Figure 10: Schematic flow diagram of Lirima Gravity Flow Scheme. Variable inputs required for water treatment are marked in green (coagulant chemical), red (disinfectant chemical), and yellow (energy). Backwash water is marked in blue. Based on personal notes taken by the author during the site visit on 3rd February 2020.

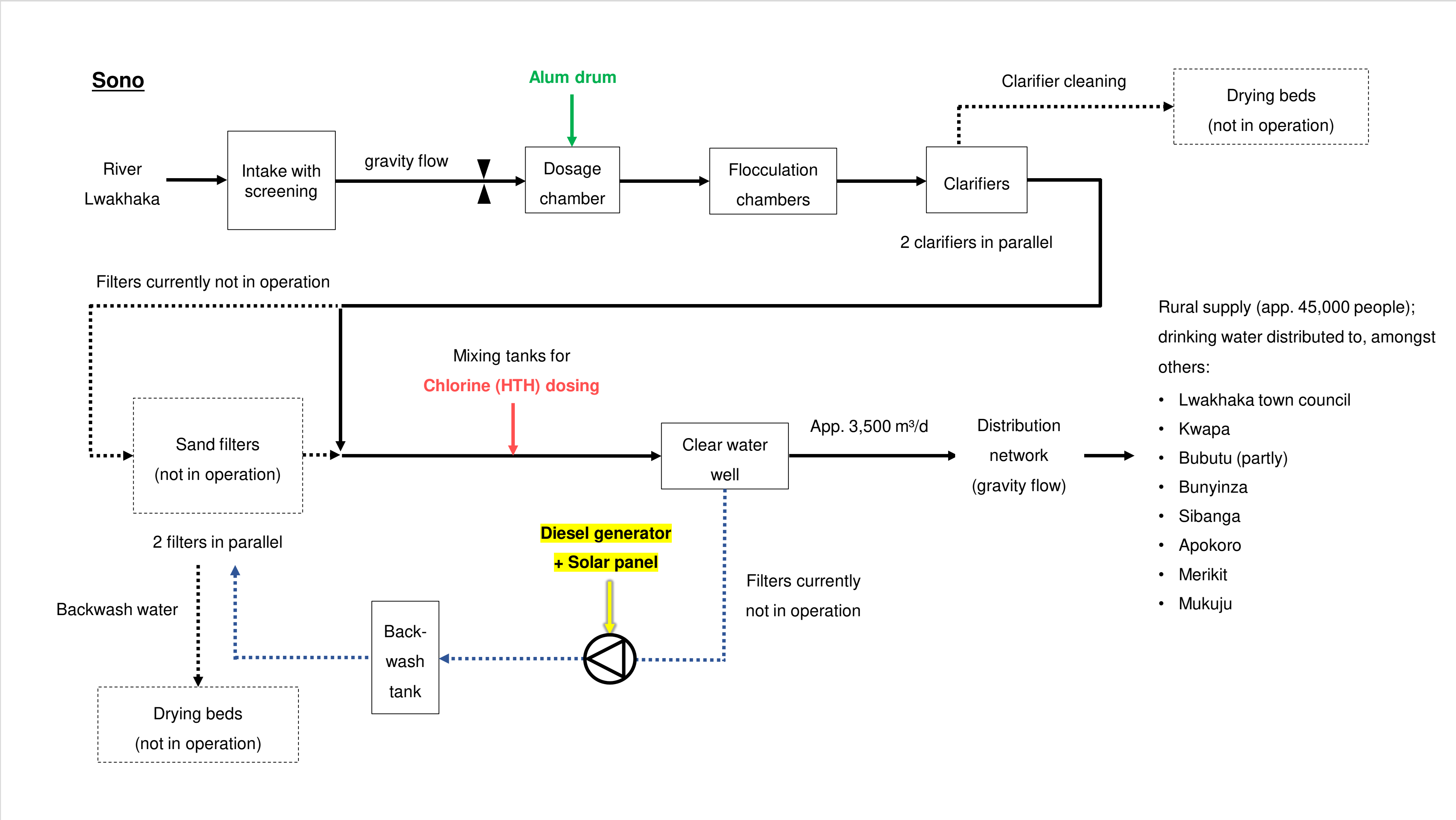


Figure 11: Schematic flow diagram of Sono Gravity Supply Scheme. Variable inputs required for water treatment are marked in green (coagulant chemical), red (disinfectant chemical), and yellow (energy). Backwash water is marked in blue (not in use at the time of the site visit). Based on personal notes taken by the author during the site visit on 3rd February 2020.

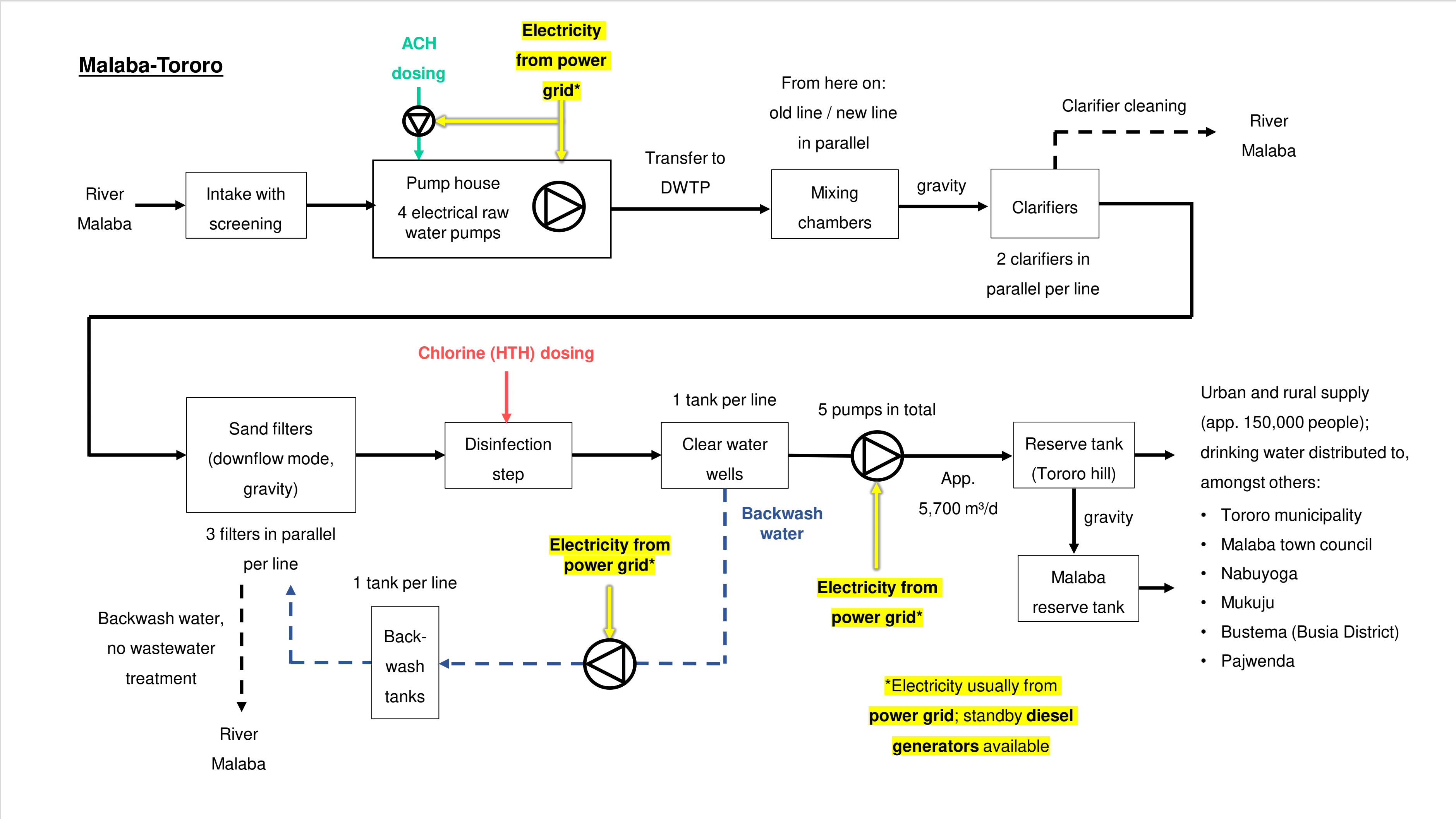


Figure 12: Schematic flow diagram of Malaba-Tororo Water Supply. Variable inputs required for water treatment are marked in turquoise (coagulant chemical), red (disinfectant chemical), and yellow (energy). Backwash water is marked in blue. Based on personal notes taken by the author during the site visit on 4th February 2020.

Even though the case study DWTPs follow the same principal treatment approach, they vary in the applied coagulant chemical type. While Sono and Lirima apply alum, Malaba-Tororo uses ACH, as the figures above show. According to Moses Butele, ACH is generally used at DWTPs with poor raw water quality or high production volumes since it is a more effective and potent coagulant, resulting in lower required doses compared to other coagulants. He states that this notion was confirmed empirically by NWSC by jar test experiments and long-term experience. According to John Ogire, this higher effectivity is the main reason for the use of ACH at Malaba-Tororo. He mentions that it was possible to use alum at the DWTP as well, but that this would result in extremely high coagulant chemical requirements. Moses Butele reports that the use of ACH has economic advantages and prevents overworking of dosing pumps at high production plants. Another advantage is that ACH does not change the pH of processed water as much compared to other coagulants, i.e., treated water is not as acidic as it would be in case of alum (over-)dosing. According to Moses Butele, this allows to save pH adjusters such as soda ash to correct the pH, which would result in another cost factor at the DWTPs. Furthermore, he mentions that ACH is easier to handle, as it does not require dilution with water before use. During the mixing of alum with water, dust can occur that may be inhaled by the treatment plant staff, potentially resulting in lung problems. This effect is not observed with ACH.

All coagulant chemicals used at the case study DWTPs are imported. According to John Ogire, alum arrives from Kenya, and ACH from South Africa. He states that a constant supply of both chemicals is secured. Based on notes in the record books, different types of ACH were used at the DWTP of Malaba-Tororo during the observation period, namely Zetafloc USP34 (see monthly data collection for April 2018 and record book "Pumpages and Chemical used", sheet for June 2018), Zetafloc 2300 (see monthly data collection for April 2019), and Zetafloc 2300L (see monthly data collection for August 2017).

Real-time control and process monitoring is available at none of the case study DWTPs, neither for water quality, nor for operating parameters. Nevertheless, dosing decisions for coagulant chemicals are frequently due in short time intervals which do not allow to perform jar test experiments in advance, particularly at the upstream DWTPs of Lirima and Sono. Therefore, plant operators decide for suitable dosages based on their professional experience under consideration of the weather conditions and verify these dosing decisions afterwards with jar test experiments. In practice, a comparatively constant or fix amount of coagulant chemical is dosed to the raw water at the beginning of the treatment trains in dry conditions. In case of rainfall, the coagulant dose is increased to react to the expected increase in sediment and particle contents in the raw water. According to the plant overseers, rainfall in the areas of Lirima and Sono leads to a direct increase of the alum dosage at the respective DWTPs, i.e., without any time delay. At Sono, operations are even interrupted as a precaution in case of subjectively excessive rainfalls. When the rain ends, the alum dose is decreased again. For Lirima, the plant overseer reports about approximately 20 kg of alum used per dry day and 25 kg per rainy day. At Sono, between 50 and 150 kg of alum use are reported per day, depending on the weather conditions. Unfortunately, only twelve individual jar test protocols (from Lirima DWTP) were available to the author. Hence, it was not possible to systematically determine potential deviations between de facto and optimal coagulant doses. In contrast to Lirima and Sono, the effect of rainy weather on water quality arrives with a delay of about four to five hours at the DWTP of Malaba-Tororo. This allows for the plant staff to react and to perform jar test experiments to determine and apply optimum coagulant dose rates, which is not possible for the staff of Lirima and Sono.

As disinfectant chemical, Chlorine High Test Hypochlorite (HTH) is used at all case study DWTPs. Tito Amuku states that the applied chlorine concentration stays nearly constant, i.e., that the dose increases or decreases mainly according to the volume of processed water. He reports that approximately 3.5 kg of chlorine per day are used at Lirima DWTP, regardless of the weather conditions. A similar approach is reported by Sara Mbabazi for Sono. Here, the optimum chlorine dosage is determined by chlorine demand tests and then kept nearly constant. Sara Mbabazi reports about approximately 4 to 6 kg of chlorine use per day at Sono DWT, depending on the volume of processed water. No average numbers were mentioned for Malaba-Tororo.

The DWTPs of Lirima and Sono are located in altitudes of approximately 1,912 and 1,571 m MSL, respectively (Herrnegger 2020, p. 2). As gravity flow schemes, they take advantage of elevation differences and their higher position relative to the supplied areas. Thereby, no pumps are required to divert abstracted water from the source streams to the DWTPs, and to distribute produced drinking water to the users located at lower altitudes. In contrast, Malaba-Tororo is at a lower altitude of approximately 1,118 m MSL (Herrnegger 2020, p. 2) and hence requires pumping.

Depending on the respective DWTP, the energy required to operate the pumps and other facilities is produced by solar panels, fuel generators, and/or is provided by the electricity grid. As Figure 10 illustrated, the energy for Lirima is generated by solar panels and a backup petrol generator. According to Tito Amuku, the solar panels produce about 40 kWh/d, depending on the sunshine on the respective day. For the petrol generator, about 20 L of fuel are used in average per week. Besides requirements for lighting, office and staff spaces, and laboratory, the energy mainly supplies the backwash water pumps. At the DWTP of Sono, the situation is similar. As shown in Figure 11, the required energy is provided by solar panels and a diesel generator. According to Sarah Mbabazi, about 20 L of diesel are used in average per week. In contrast to Lirima and Sono, the DWTP of Malaba-Tororo is connected to the electricity grid and has standby diesel generators, as indicated in Figure 12. The diesel generators cover regular power outages of about 28 hours per month, which results in higher costs for energy provision as diesel fuel is expensive in comparison to electricity from the power grid. Besides lighting, laboratory, and office and staff, the electricity at Malaba-Tororo is used for various pumps at four individual locations throughout the treatment train (see Figure 12), including:

- four electrical pumps in the pump house to draw in raw water from river Malaba (two in operation, two in standby),
- three electrical dosing pumps in the pump house to apply coagulant chemical to the raw water (one in operation, two in standby),
- two electrical backwash pumps to transfer water from the clear water wells to the backwashing tanks (i.e., service water pumps) (one in operation, one in standby),
- and five electrical pumps to transfer water from the clear water wells to the reserve tank on Tororo hill, before it is distributed by gravity to the water users (two to three in operation, two to three in standby).

Due to its higher plant capacity (see Chapter 4.2.3) and several energy-consuming components, the operation of Malaba-Tororo requires considerably more energy compared to Lirima and Sono. The two DWTPs located upstream have lower energy demands due to their smaller production capacities, and since they operate in gravity supply mode which reduces the number of pumps required. Besides these differences, the DWTPs face similar challenges regarding the energy supply, particularly during the wet seasons. According to Tito Amuku, missing power for backwashing of the sand filters regularly results in an interruption of operations or impaired final water qualities. John Ogire mentions challenges at Malaba-Tororo with regards to electro-mechanical failures of pumps and hydroelectric power failures.

According to Moses Butele and John Ogire, energy consumption records are compiled by the respective plant engineers at the DWTPs. However, these records were not shared with the author. Therefore, no systematic evaluation of energy consumption at the case study DWTPs could be made.

According to the plant overseers, Lirima supplies approximately 50,000 and Sono 45,000 people[6]. The supplied settings are mainly rural, while urban areas in the form of town councils are envisaged for provision in the future. John Ogire states that Malaba-Tororo supplies about 150,000 people with drinking water, including rural and urban settings such as Tororo and Malaba town.

Regardless of the challenges described for the DWTPs in the SMMRB, the processed final water should in any case conform to the national standards for potable water. For Sono, this requirement was mentioned as a challenge, particularly regarding the parameters apparent colour and turbidity. If too much silt is contained in the raw water, the treatment process is not always sufficient to produce a final water that adheres to the standards. Sometimes, the plant operators see no other option than to interrupt the supply, which leads to supply outages.

At Lirima, the wastewater after backwashing and cleaning of clarifiers is treated in drying beds on-site of the DWTP. At Sono, drying beds are available, but were not in operation at the time of the site visit. The initial design at Malaba-Tororo was to purify the wastewater in a natural wetland located nearby (i.e., a natural engineered treatment system). This is not done anymore today. Instead, the wastewater is sent back to river Malaba without wastewater treatment.

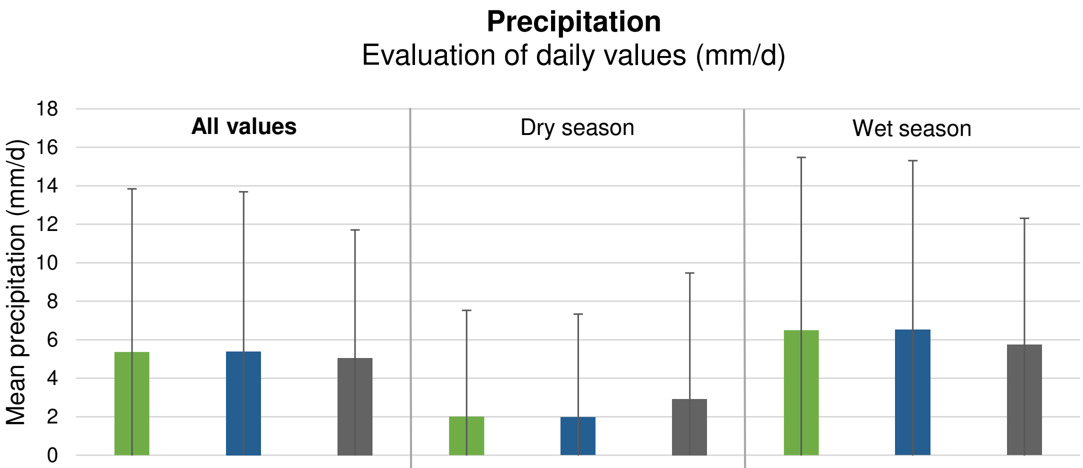
4.2. Evaluated parameters

4.2.1. Precipitation

As described in Chapter 2.1.3, the SMMRB receives a bi-modal rainfall pattern with average rainfalls between 700 mm and more than 2,000 mm per year, depending on the specific location within the river basin. The dry season typically extends from December to February and the wet season from March to November, including two rainfall peaks in April and October. Following this allocation of months to dry and wet seasons, Figure 13 shows average daily precipitation values and related statistical parameters for the relevant upstream catchment areas of Lirima, Sono, and Malaba-Tororo. On the left, the figure shows all daily values from the observation period (here: 18th September 2016 to 31st December 2019); in the middle, only the dry season (December to February) is

[6] The literature indicates contradicting numbers for the population supplied by Lirima and Sono of between 31,804 and 179,000 people for Lirima (Government of Uganda 2019, p. 31; Watala 2018), and of 39,000 people for Sono (Juma 2011). A simple control calculation by the author showed that particularly the numbers for Sono should be considered cautiously, as they indicate comparatively high water supply rates per person. This might be associated with an overestimation of the processed water volumes, or an underestimation of the service population.

included, and on the right, only the wet season (March to November) is considered. This approach is retained in the following subsections for the other raw water quality and operating parameters considered.



	All values			Dry season			Wet season		
	Lirima	Sono	Malaba-Tororo	Lirima	Sono	Malaba-Tororo	Lirima	Sono	Malaba-Tororo
Mean	5.37	5.39	5.04	2.01	1.97	2.93	6.50	6.53	5.75
SD	8.47	8.30	6.68	5.52	5.36	6.55	8.98	8.79	6.57
Min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Max	63.74	62.51	43.39	40.84	36.93	32.49	63.74	62.51	43.39
Median	0.00	0.61	2.32	0.00	0.00	0.00	2.71	2.74	4.30
n (-)	1,200	1,200	1,200	301	301	301	899	899	899

Figure 13: Statistical evaluation of daily values for precipitation in the relevant upstream areas of Lirima, Sono, and Malaba-Tororo DWTPs during the observation period (18th September 2016 to 31st December 2019). Data is based on CHIRPS and was provided by Dr. Mathew Herrnegger.

In comparison to Lirima and Malaba-Tororo, the relevant upstream area of Sono receives the highest average precipitation with 5.39 mm per day (1,966 mm per year). The scheme also shows the highest precipitation during the wet season of 6.53 mm per day. For both cases, Lirima shows only slightly lower precipitation values, while Malaba-Tororo shows considerably smaller values. The differences between Sono and Malaba-Tororo are at 0.35 mm per day (-6.5 %) for all days and at 0.78 mm per day (-11.9 %) during the wet season. Interestingly, Sono is at the same time the scheme with the lowest mean precipitation value for the dry season of 1.97 mm per day. Here, Malaba-Tororo shows the highest precipitation values with 2.93 mm per day, which is about one third (0.96 mm per day or 32.8 %) more compared to Sono. As the figure shows, all data categories are subject to comparatively high standard deviations that are bigger than the respective mean values. This indicates that daily precipitation values are relatively dispersed and spread out for each time series. This notion is underlined by the box plot diagram for all precipitation values in Figure 14. A box plot diagram shows the minimum, median, maximum, and outlier values for each case, as well as the lower (25 %) and upper (75 %) quartiles and the lower and upper whiskers. The figure shows that the lower whiskers and lower quartiles are at 0.00 mm per day for each of the upstream areas, and so is the median of Lirima. Therefore, only upward outliers exist. The highest value measured during the observation period was at 63.74 mm per day at Lirima's relevant upstream area, followed by 62.51 mm per day at Sono. Both maximum values occurred on 23rd November 2019. The maximum of Malaba-Tororo is considerably lower with 43.39 mm on the 23rd April 2019. Due to the reliable data, no outlier analysis was carried out for the precipitation data series.

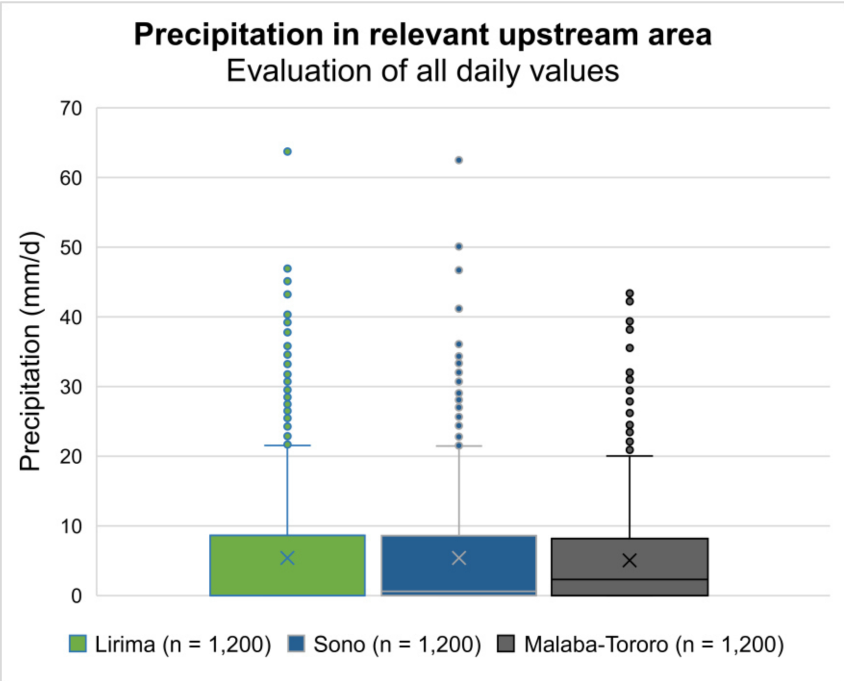


Figure 14: Box plot diagram of all available daily values for precipitation in the relevant upstream areas of Lirima, Sono, and Malaba-Tororo DWTPs during the observation period (18th September 2016 to 31st December 2019).

Figure 15 shows the development of precipitation over time in the relevant upstream catchment areas of Lirima, Sono, and Malaba-Tororo. In general, it becomes clear that the three data series show a comparable progression throughout the observation period. Particularly the curves for Lirima and Sono are almost identical for large shares of the considered time. Malaba-Tororo stands out with lower values occasionally, e.g., from June to October 2017 or from June to October 2019. In terms of seasonality, the diagram generally shows compliance with the long-term seasonal trends identified for the SMMRB, e.g., the dry months are centred around January and the wet months extend from March to November, including two distinct peaks. The highest precipitation values occur in October 2019, for example 418.21 mm for Sono. In comparison, the maximum precipitation in 2017 is considerably lower with 301.16 mm per month (-28.0 %) at Sono. The contrast between the second yearly peaks in 2018 and 2019 is also remarkable, with October 2018 having only about half as much (50.2 %) precipitation as October 2019. As these numbers suggest, the year 2019 shows the highest yearly precipitation in the period 2017-2019. For Sono, precipitation sums for the years 2017, 2018, and 2019 were at 1,981 mm, 1,934 mm, and 2,185 mm, respectively. A similar trend is observed for Lirima. For Malaba-Tororo, the contrast between the years was even greater, with yearly precipitation sums of 1,833 mm, 1,779 mm, and 2,097 mm, respectively. That means that in 2018, total precipitation in the relevant upstream area of Malaba-Tororo was 318 mm (15.2 %) lower compared to 2019.

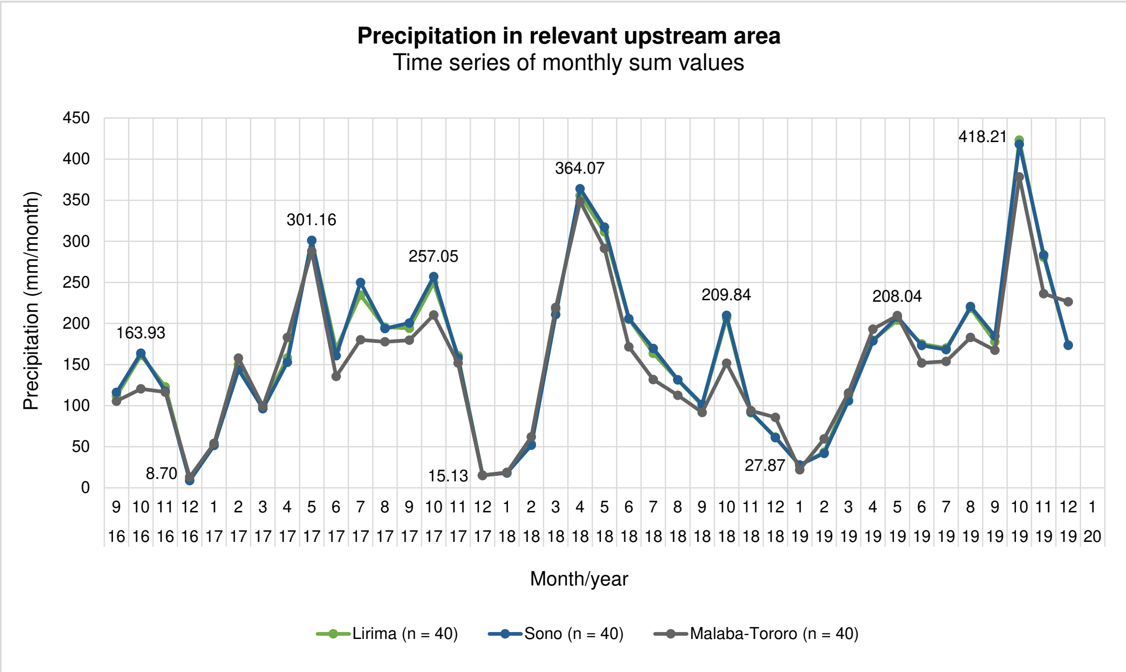


Figure 15: Time series diagram of monthly precipitation in the relevant upstream areas of Lirima, Sono, and Malaba-Tororo, September 2016 to December 2019. All point labels belong to Sono.

These observations indicate a clear variability regarding precipitation in the observation period, as the rainfall patterns show distinct deviations between the years. Individual months are not in every case comparable with months from other years. Consequently, also deviations from the observation period to the long-term precipitation mean can be observed. Figure 16 shows the monthly precipitation relative to the long-term monthly mean in the relevant upstream areas of Lirima, Sono, and Malaba-Tororo. The long-term monthly mean was calculated based on precipitation averages for each month over a period of 39 years (1981-2019). While a value of 100 % stands for a monthly precipitation consistent with the long-term average, values above 100 % indicate wetter conditions, and vice versa. The figure indicates that several months have precipitation sums almost identical to the long-term expected value, e.g., June and November 2017 or July and December 2018. From May 2018 to September 2019, precipitation was comparatively close to the expected values, with no value exceeding +50 % or falling below -50 % of the long-term monthly mean at Lirima and Sono. Nevertheless, also larger deviations can be observed that underline the precipitation variability and exceptionally high monthly rainfall sums during the observation period described above. For the example of Sono, these include unexpected precipitation values of 221 % in February 2017 and 294 % in December 2019 – months that usually belong to the dry season. The precipitation peak in October, per se a high value in comparison to other months, amounts to 191 % of the long-term average in 2019. While upward deviations are more numerous and occur up to a tripling of the values (December 2019), downward deviations are modest. The highest shortfall within the observation period occurred in December 2017 with only 26 % of the long-term monthly mean precipitation, i.e., 15.13 mm per month, for the example scheme of Sono.

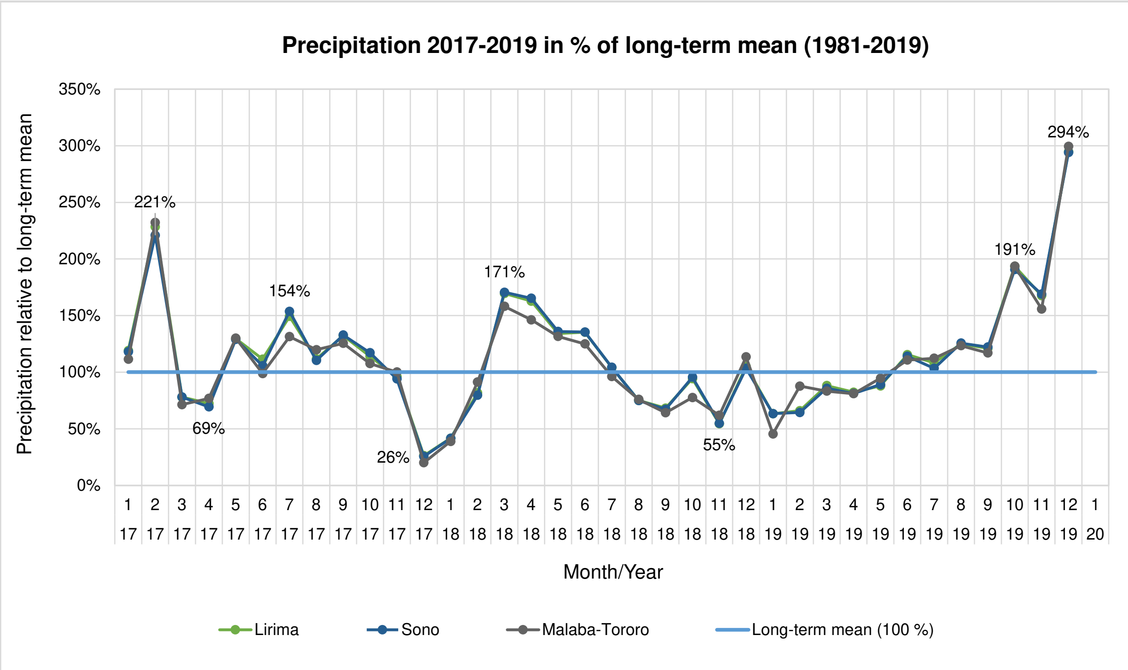
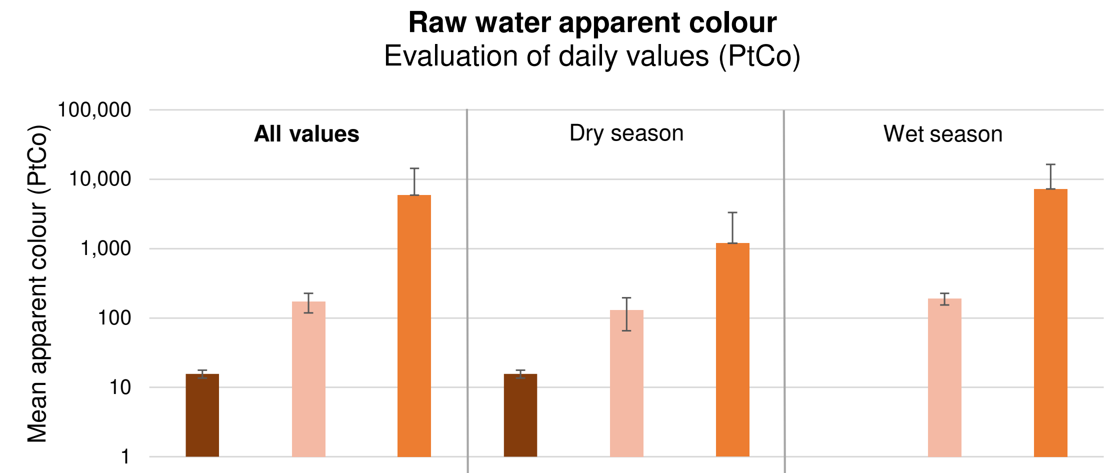


Figure 16: Time series diagram of monthly precipitation relative to the long-term monthly mean (1981-2019) in the relevant upstream areas of Lirima, Sono, and Malaba-Tororo, January 2017 to December 2019. Values above 100 % indicate wetter conditions compared to the long-term monthly mean, and vice versa. All point labels belong to Sono.

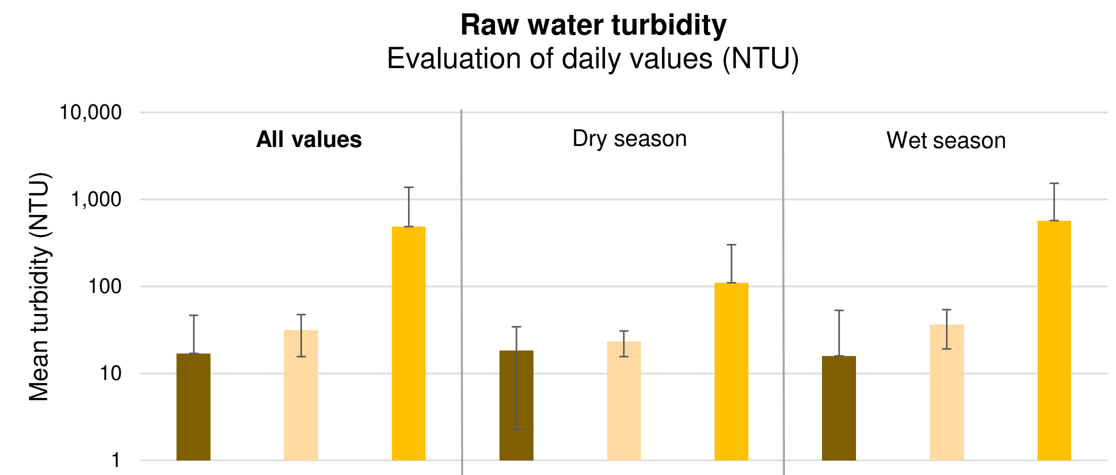
4.2.2. Raw water quality

As described in Chapter 4.1, John Ogire observed long-term changes in surface water quality in the SMMRB in terms of a noticeable increase in siltation in streams due to agricultural activities, particularly in plants located in downstream areas of the river basin. Consequently, raw water apparent colour and turbidity at the DWTP intakes would increase. According to John Ogire, peak values of apparent colour and turbidity during the wet season amount to 30,000 PtCo and 2,800 NTU, respectively. As the quantitative data provided by NWSC shows, these values are even exceeded. Figure 17 and Figure 18 present statistical evaluations for apparent colour and turbidity at the intakes of Lirima, Sono, and Malaba-Tororo DWTPs, i.e., for their raw water.



	All values: Lirima	All values: Sono	All values: Malaba-Tororo	Dry season: Lirima	Dry season: Sono	Dry season: Malaba-Tororo	Wet season: Lirima	Wet season: Sono	Wet season: Malaba-Tororo
Mean	15.67	172.43	5,898.91	15.67	130.22	1,199.79	-	190.52	7,262.45
SD	2.08	53.68	8,453.86	2.08	64.69	2,112.64	-	36.86	9,092.92
Min	14	69	129	14	69	129	-	132	149
Max	18	250	90,300	18	240	11,400	-	250	90,300
Median	15	175	2,910	15	123	510	-	198	4,090
n (-)	3	30	538	3	9	121	0	21	417

Figure 17: Statistical evaluation of available daily values for raw water apparent colour at the DWTPs of Lirima, Sono, and Malaba-Tororo. Y-axis in logarithmic scale. Data provided by NWSC in hard copy form.



	All values: Lirima	All values: Sono	All values: Malaba-Tororo	Dry season: Lirima	Dry season: Sono	Dry season: Malaba-Tororo	Wet season: Lirima	Wet season: Sono	Wet season: Malaba-Tororo
Mean	17.00	31.58	488.93	18.31	23.19	110.59	15.89	36.56	572.93
SD	29.54	15.94	893.51	16.05	7.55	190.70	37.36	17.46	963.85
Min	1.06	7	9.26	1.06	7	9.26	2.06	11	44
Max	300	150	8,830	75	40	1,020	300	150	8,830
Median	10	30	203	10	25	37	10	30	254
n (-)	303	258	666	139	96	121	164	162	545

Figure 18: Statistical evaluation of available daily values for raw water turbidity at the DWTPs of Lirima, Sono, and Malaba-Tororo. Y-axis in logarithmic scale. Data provided by NWSC in hard copy form.

Regarding apparent colour, it is important to note upfront that the number of observations (n) for both Lirima and Sono are very low, as Figure 17 shows. The quantitative database provided only three daily values for Lirima, and 30 for Sono. Therefore, these data series should be considered with reservations, as they are considerably less informative than the one of Malaba-Tororo with 538 daily values. It is doubtful that the apparent colour data series of Lirima and Sono represent the true variability in the raw water, as they both include only a small fraction of potential 1,231 days during the observation period. This issue gets even more evident for the dry and wet seasons. Due to the temporal distribution of the original data, only nine daily values are available for Sono for the dry season, i.e., for days from December to February. For the wet season, 21 daily values exist for Sono, but not a single value for Lirima. Therefore, no statements can be made for Lirima for the wet season.

In comparison to apparent colour, considerably more daily turbidity values were provided for the case study DWTPs, as Figure 18 shows. For every case evaluated, at least 96 daily values are included in the calculation of mean values. Hence, this parameter seems to be better suited to reflect the raw water conditions in the SMMRB, and statements based on the parameter promise to be more reliable. In general, the data availability is best for Malaba-Tororo with 538 daily apparent colour values and 666 daily turbidity values. As shown in Table 3, the original data used to calculate the mean values comes from different points in time. However, all available daily data was used to calculate the numbers in Figure 17 and Figure 18 (as well as in the upcoming figures), independent of the date. When comparing raw water apparent colour and turbidity at the DWTPs with each other, these time differences create inaccuracies. Since data from different points in time is compared, different environmental factors present in the SMMRB such as precipitation, temperature, evapotranspiration, season, vegetation cover, or planting season were included in the calculation that influence apparent colour and turbidity. As described in the methodology, this procedure is nevertheless used to obtain an estimate for the water quality parameters and to allow for a comparison between the DWTPs.

That said, Figure 17 and Figure 18 show that the averages of all available values increase from Lirima via Sono to Malaba-Tororo, i.e., increase the more downstream the DWTP is located within the SMMRB. The same impression can be retrieved from the evaluations for the dry season and (where possible) the wet seasons. The relative differences between the three DWTPs are clearly pronounced, which should not be confused due to the logarithmic scale applied in the figures. While Lirima shows a mean apparent colour of 15.67 PtCo, Sono's value of 172.43 PtCo is already eleven times larger, and Malaba-Tororo has a mean value of 5,898.91 PtCo, which is 376 times the value of Lirima. This trend is not as pronounced in terms of raw water turbidity. Lirima shows a mean turbidity of 17.00 NTU, while Sono's mean value of 31.58 NTU is not even twice as much. Malaba-Tororo has a mean turbidity of 488.93 NTU, which is about 29 times the value of Lirima.

In general, the described relationship can be observed in the dry and wet seasons as well. As expected, the raw water qualities at Sono and Malaba-Tororo are considerably better in the dry season compared to the wet season. Sono shows mean apparent colours of 130.22 PtCo in the dry and 190.52 PtCo in the wet season, respectively, resulting in a difference of about 46 %. For turbidity, this difference is at 58 %. At Malaba-Tororo, the seasonal difference is more pronounced. For apparent colour, mean values are at 1,199.79 PtCo in the dry and 7,262.45 PtCo in the wet season, resulting in a difference of about 600 %. For turbidity, the mean value in the wet season of 572.93 NTU is about five times higher than the one for the dry season of 110.59 NTU. In contrast, the mean turbidity value for Lirima is higher during the dry season (18.31 NTU) compared to the rainy season (15.89 NTU). This relationship is unexpected, since increased precipitation in the catchment would usually result in higher turbidity values in stream water (see Chapter 2.2.3). The results suggest that precipitation in the relevant upstream catchment area of Lirima has a smaller or no impact on raw water quality. However, due to a comparatively small difference of only 2.42 NTU between dry and rainy season, this phenomenon might also be due to measurement inaccuracies or other environmental influences.

Figure 19 and Figure 20 show box plot diagrams for raw water apparent colour and turbidity at the case study DWTPs. The fact that Lirima has only three apparent colour values discussed before results in a very narrow box of lower and upper quartiles and hardly visible whiskers. The scale of the diagram for Malaba-Tororo had to be adjusted for both water quality parameters due to different orders of magnitude measured at the DWTP. Therefore, the boxes of lower and upper quartiles are largest at Malaba-Tororo. The diagrams illustrate that no downward outliers exist in any of the evaluated data series and that also no upward apparent colour outliers exist for Lirima and Sono. However, Malaba-Tororo has several upward outliers that are all in higher orders of magnitude than in the other two DWTPs. The highest values measured during the observation period were at 90,300 PtCo for apparent colour and at 8,830 NTU for turbidity. These values at Malaba-Tororo exceed the peak values indicated by John Ogire, 30,000 PtCo and 2,800 NTU, by about a factor of three each. In comparison to these high values at Malaba-Tororo, the maximum values at Lirima and Sono are much lower. For example, maximum raw water turbidities were at 300 NTU and 150 NTU for Lirima and Sono, respectively. All turbidity maxima occurred during the wet season. Due to the high variability of the data, an outlier analysis was carried out for the precipitation data series.

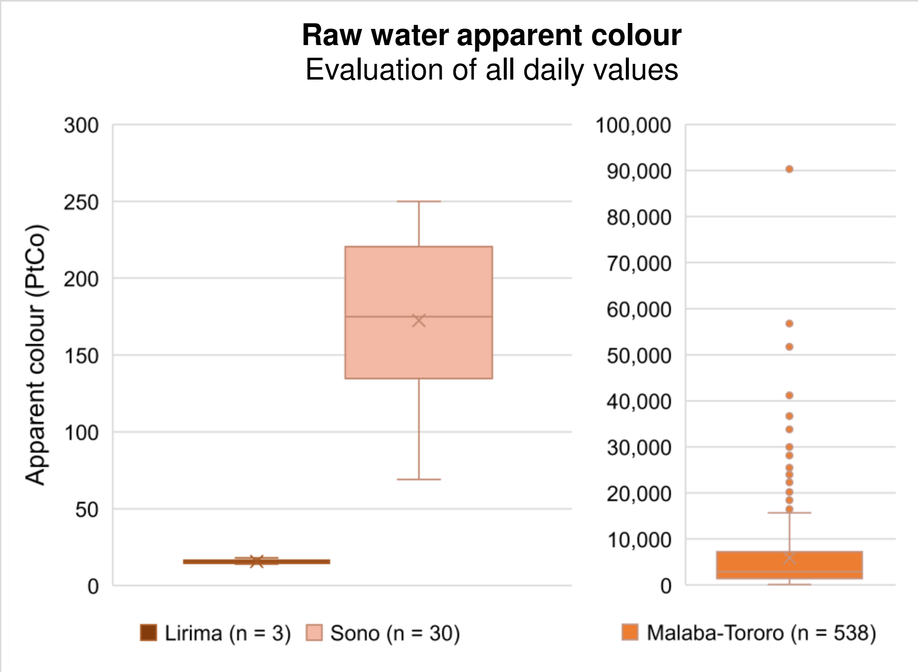


Figure 19: Box plot diagrams of all available daily values for raw water apparent colour and raw water turbidity for Lirima and Sono DWTPs.

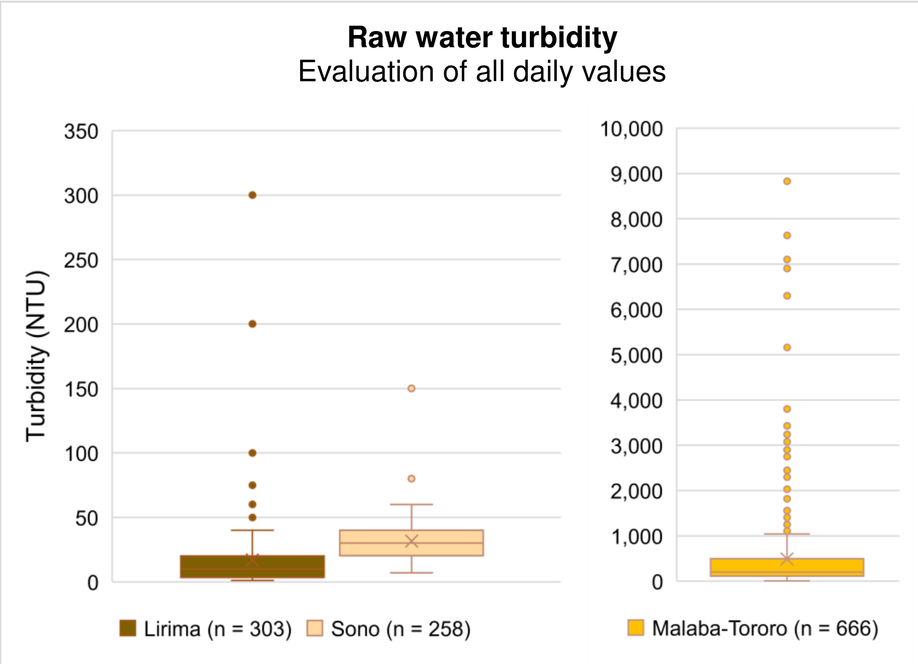


Figure 20: Box plot diagrams of all available daily values for raw water apparent colour and raw water turbidity for Malaba-Tororo DWTP.

The described turbidity maxima can be identified in the time series diagram in Figure 21 as well. The diagram shows the development of daily turbidity at the intakes of the case study DWTPs over time. While the maximum turbidity for Malaba-Tororo occurred in the first yearly peak in 2017 (21st March), the maxima of Lirima and Sono both occurred in 2018 (4th and 6th March and 3rd September, respectively). Overall, a clearly pronounced and repetitive temporal pattern can be observed for Malaba-Tororo, with peaks occurring around March/April and October and minima around January. The lowest turbidities were measured for Malaba-Tororo on 3rd February 2017 (9.26 NTU), for Lirima on 3rd February 2018 (1.06 NTU), and for Sono on 22nd and 24th January 2020 (7 NTU) – all in the dry season. Furthermore, the diagram shows that the available data originates from different points in time, which do not necessarily overlap. While the data series for Malaba-Tororo is comparatively consistent, providing daily observations from 1st January 2017 to 30th November 2018 (n = 666), Lirima and Sono show less observations and lower continuity. Lirima's data series (n = 303) starts on 29th November 2017 and ends on 23rd April 2019. Repeatedly, major temporal interruptions without any daily observations occur, e.g., from 29th July to 31st August 2018 (34 days) or from 23rd November to 31st December 2018 (39 days). A similar observation can be made for the data series of Sono (n = 258). Its first and last measurements were made on 3rd July 2018 and 30th January 2020, respectively. Temporal interruptions of the data series exist, for example, from 4th October to 4th December 2018 (62 days) or from 29th April to 26th September 2019 (151 days). Such data gaps might be due to several reasons, including that the respective record sheets exist but were not provided to the author, or that no measurements were taken on-site the treatment plant during the respective periods.

Moreover, Figure 21 illustrates that the turbidity data series of Lirima and Sono contained widespread repetitions of specific numbers. This results in steady distributions of observations in the figure, visible as areas in which data points seem to follow imaginary horizontal lines. In the data series of Lirima, turbidities of exactly 40 NTU (n = 42), 20 NTU (n = 26), 15 NTU (n = 40), and 10 NTU (n = 53) were observed repeatedly. For example, the latter value of 10 NTU alone represents about 17 % of the whole data series, while all four turbidity levels together make up for more than half of it. For Sono, a similar observation can be made. Turbidities of exactly 60 NTU (n = 17), 50 NTU (n = 23), 40 NTU (n = 23), 30 NTU (n = 79), 25 NTU (n = 33), 20 NTU (n = 24), and 15 NTU (n = 11) are each observed unexpectedly often. The turbidity level of 30 NTU accounts for 31 % of the whole data series, while together, the listed turbidity levels make up for more than 80 % of it. It is noteworthy that all values are whole numbers and multiples of 5. In terms of their temporal distribution, the discussed values are largely grouped together and form certain clusters, extending from December 2017 to September 2018 for Lirima, and from August 2018 to April 2019 for Sono. The values that follow these clusters, respectively, do not seem to fulfil the observation described before. An explanation for these observations could not be determined based on the data. Possibly, they originate from inaccurate measurements followed by rough rounding. In any case, it must be assumed that in reality, more variable turbidites were present in the raw water on the respective days.

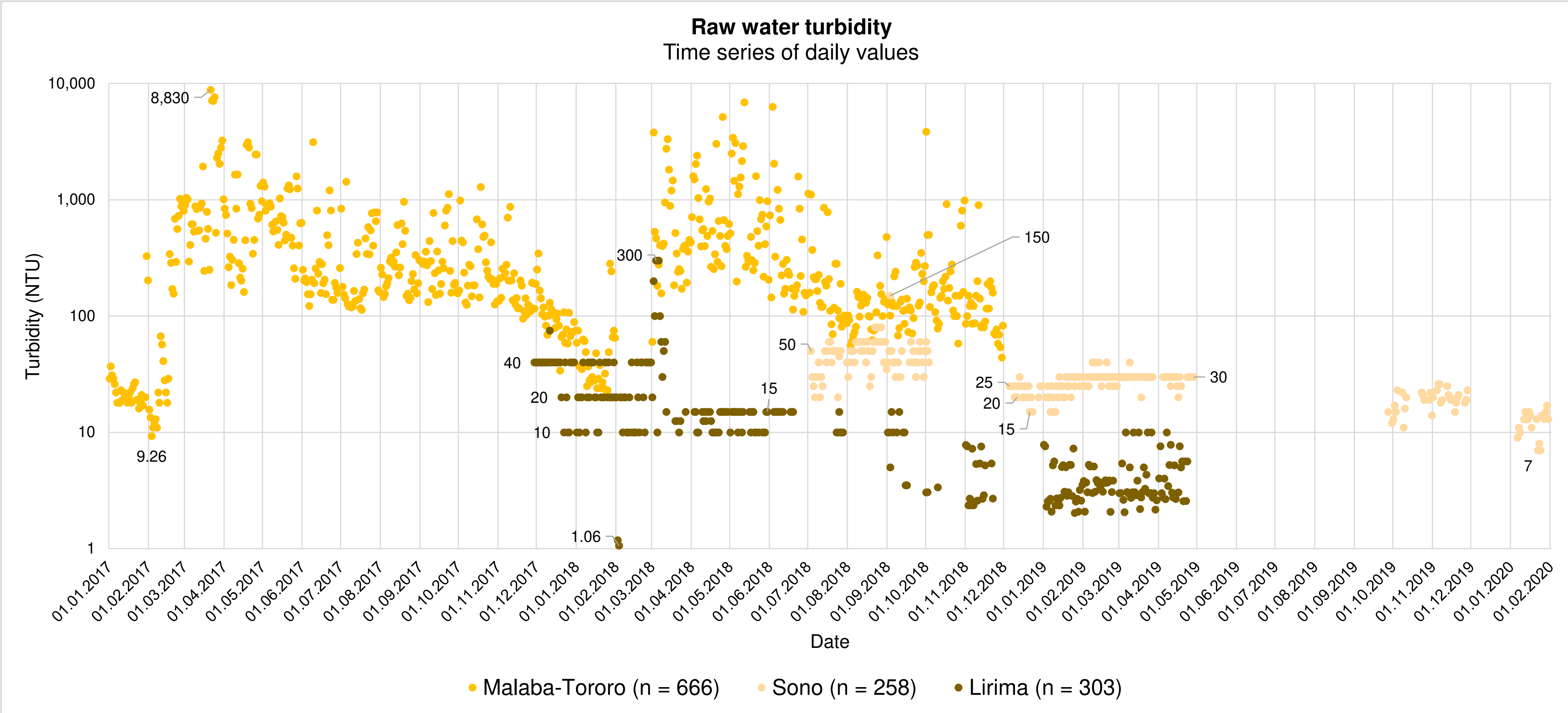


Figure 21: Time series diagram of all daily values for raw water turbidity at the DWTPs of Lirima, Sono, and Malaba-Tororo, January 2017 to January 2020. Y-axis in logarithmic scale.

When shifting from daily to monthly resolution, the time series diagrams in Figure 22 for apparent colour and Figure 23 for turbidity are created. In the turbidity diagram, the basic course and relationships that were observable in Figure 21 are depicted as well, which can be traced particularly well for the time series of Malaba-Tororo. Yet, the previously observed patterns of repeating values at Lirima and Sono disappear due to the aggregation to monthly values. After the expansion of data (see Chapter 3.4.2), further monthly data points are included in the diagrams for which daily values were missing. Examples are any values before July 2018 for Sono, or after November 2018 for Malaba-Tororo. Overall, both diagrams show that the data series for Malaba-Tororo include the most and most consistent information, as they provide data for more than 30 months for both parameters. In comparison, the data series for Lirima and Sono provide considerably less information, ranging from 14 to 18 monthly values. While the longest consecutive data series for Lirima consists of seven months (turbidity for May to November 2018), Sono amounts to eight months (turbidity for December 2018 to July 2019). Malaba-Tororo provides the longest consecutive data series with 26 months for apparent colour (January 2017 to February 2019) and 23 months for turbidity (January 2017 to November 2018).

Both figures underline several of the findings discussed above. For both water quality parameters, the highest values can almost always be found in the data series of Malaba-Tororo, i.e., water quality is worse at the intake of this DWTP in comparison to the other two schemes. Apparent colour peaks of comparable magnitudes occur in April 2017 (14,505 PtCo) and May 2018 (14,910 PtCo). In 2019, the yearly peak at Malaba-Tororo cannot be clearly identified due to missing data, with the highest available value in May (9,460 PtCo). Lirima's data series peaks unexpectedly in August 2018 (575 PtCo), which might be due to missing data for large parts of the observation period. The same applies to Sono, which provides a comparatively fragmented apparent colour data. Its peak is in May 2019 with 238 PtCo. Turbidity peaks can be identified in June 2018 for Lirima (161 NTU), August 2018 for Sono (53.87 NTU), and May 2019 for Malaba-Tororo (2,000 NTU). It is worth noting that the monthly peaks of raw water turbidity do not always meet with the apparent colour peaks, which might be due to measurement inaccuracies or divergent data availability. In February 2018, the all-time low in monthly turbidity at Malaba-Tororo (9 NTU) is smaller than the values of Lirima (21.87 NTU) and Sono (22.10 NTU). This is the only time that any of the monthly water quality values of Malaba-Tororo falls below those of the other two DWTPs. The lowest turbidity values at Sono and Lirima occur in December 2017 (2.48 NTU) and October 2019 (3.16 NTU). The latter appears unintuitive, as October 2019 was identified as the month with the highest precipitation (423.26 mm) during the whole observation period.

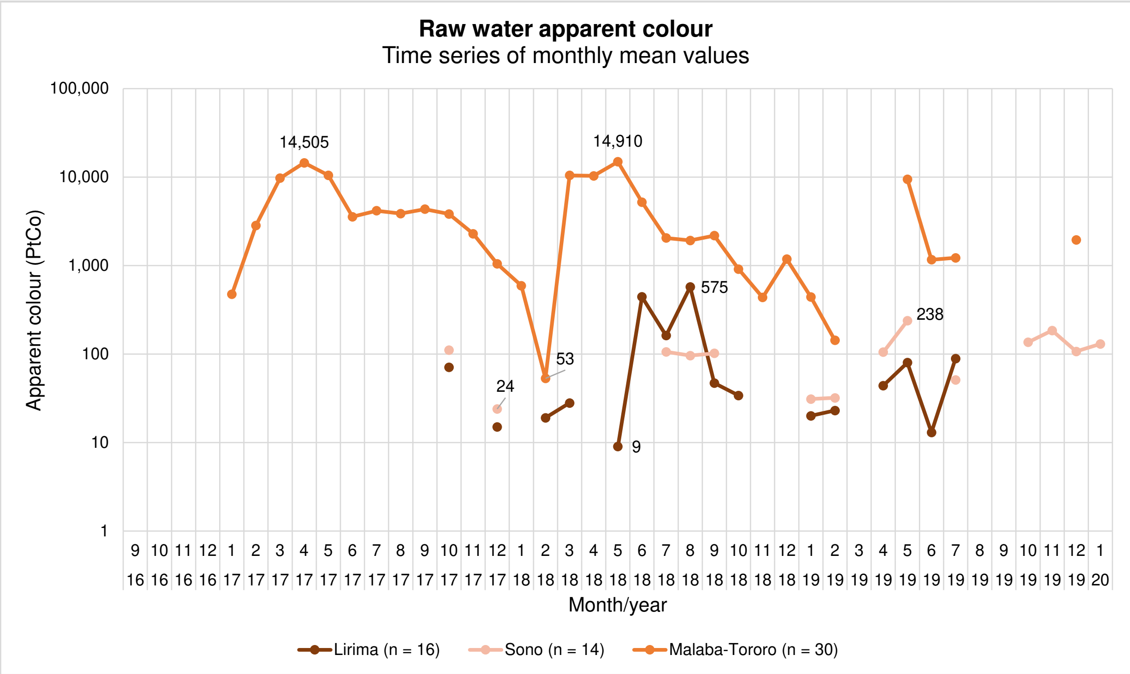


Figure 22: Time series diagram of monthly values for raw water apparent colour at the DWTPs of Lirima, Sono, and Malaba-Tororo, January 2017 to January 2020. Y-axis in logarithmic scale.

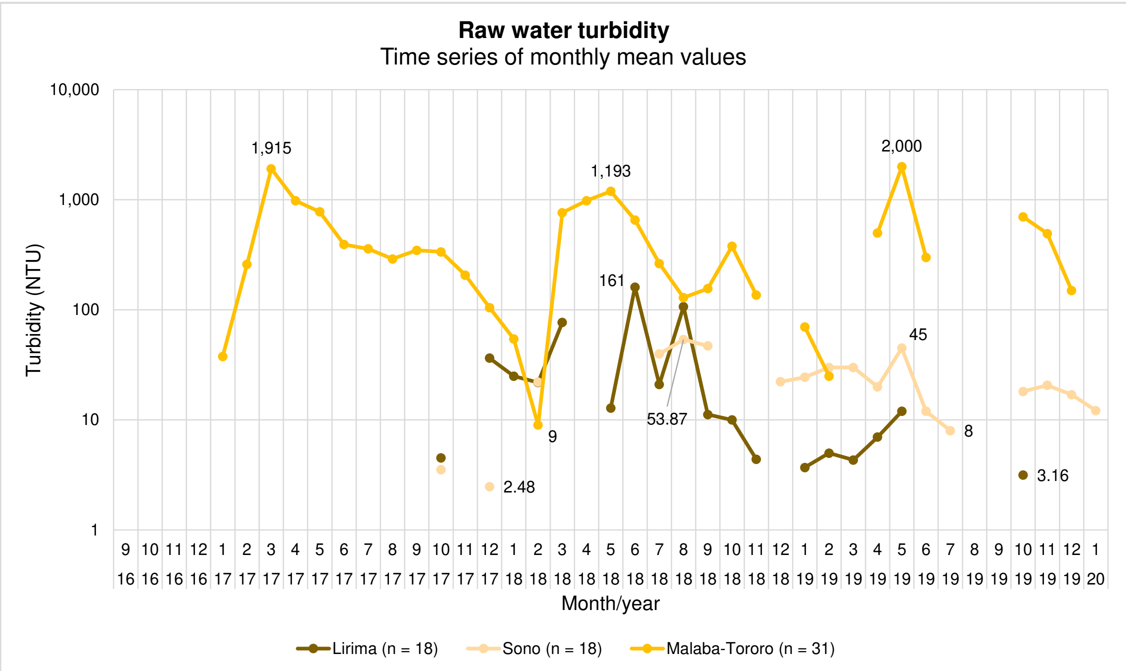


Figure 23: Time series diagram of monthly values for raw water turbidity at the DWTPs of Lirima, Sono, and Malaba-Tororo, January 2017 to January 2020. Y-axis in logarithmic scale.

Comparison with the literature

Regarding the stream water quality in the SMMRB, Ondoo et al. (2019b) determined turbidities in river Sio of 12 to 44 NTU in the dry season, and 212 to 482 NTU in the wet season. For river Malakisi, Tenge et al. (2015) found stream water turbidities between 54 and 238 NTU in the dry season, and between 60 and 289 NTU in the wet season.

The findings from the present thesis for stream water turbidity in rivers Lirima/Lwakhakha and Malaba vary depending on the sample point, i.e., the location of the respective DWTP. For example, Sono shows average raw water turbidities of 23.19 NTU in the dry season and 36.56 NTU in the wet season. While the value for the dry season fits to the findings by Ondoo et al. (2019b), the wet season value is lower compared to both mentioned publications. Malaba-Tororo shows average stream water turbidities of 110.59 NTU in the dry season and 572.93 NTU in the wet season. Here, the dry season value fits to the findings from Tenge et al. (2015), and substantially exceeds the one indicated by Ondoo et al. (2019b). The wet season value exceeds both literature findings, implying higher stream pollution at the intake point of Malaba-Tororo compared to the sampling points from the literature studies. Overall, it can be assumed that surface water quality in the SMMRB is highly dependent on the respective location along the streams. This also explains the lower turbidity values at Lirima and Sono compared to the literature, since the DWTPs are located in the headwater areas of the river basin.

Cunha et al. (2016, p. 519) observed average stream water turbidities in agricultural and industrial/urban catchments in the state of São Paulo in Brazil that were 2-3 times lower in the dry periods compared to the wet periods. For catchments dominated by agriculture, the averages for the wet and dry season were at 78 NTU and 35 NTU, respectively. In the present study, the relative differences between dry and wet season were determined to 1.58 and 5.18 at the intake points of Lirima and Malaba-Tororo, respectively. The latter shows that higher seasonal variations in stream water turbidity can be observed in the downstream areas of the SMMRB compared to the averages indicated by Cunha et al. (2016). In the upstream area, however, the observed seasonal variations were lower compared to the literature study, possibly due to limited agricultural land use upstream of Lirima.

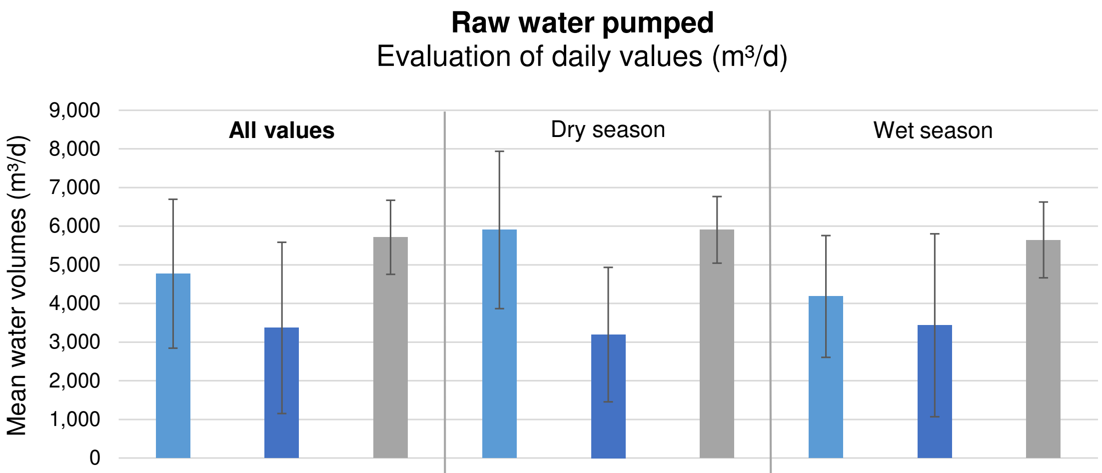
For the Phong watershed in north-eastern Thailand, Sthiannopkao et al. (2007) reported of average turbidity values of 8.87 NTU in the dry season and 316 NTU in the wet season. In comparison with the findings for the SMMRB, water quality in the Phong watershed varies more drastically between dry and wet season and shows rather low values in the dry season.

4.2.3. Water volumes

As described in the methodology (see Chapter 3.4.2), the parameters (3) raw water pumped and (4) final water produced are included in this evaluation as they are required for calculations and to get an overview of the daily production volumes at the case study DWTPs. Both parameters are measured at all case study DWTPs at suitable points of the treatment trains to capture the inflowing volumes of raw water and the outflowing volumes of purified water, respectively. The parameter (5) service water captures water volumes that are transferred from the clear water wells to the backwash tanks (see Figure 10, Figure 11, and Figure 12). According to Tito Amuku, the water from the backwash tanks is used for different purposes, including for backwashing of sand filters, flushing of sanitation facilities, cleaning of the yards, and laboratory uses. Consequently, it not possible to determine backwash water volumes solely based on the provided service water values. Service water can only serve as a representative parameter that approximates the amount of backwash water. The true backwash water volumes per day and month are likely to be less than the respective service water volumes, as they constitute only a volumetric fraction of the service water volumes.

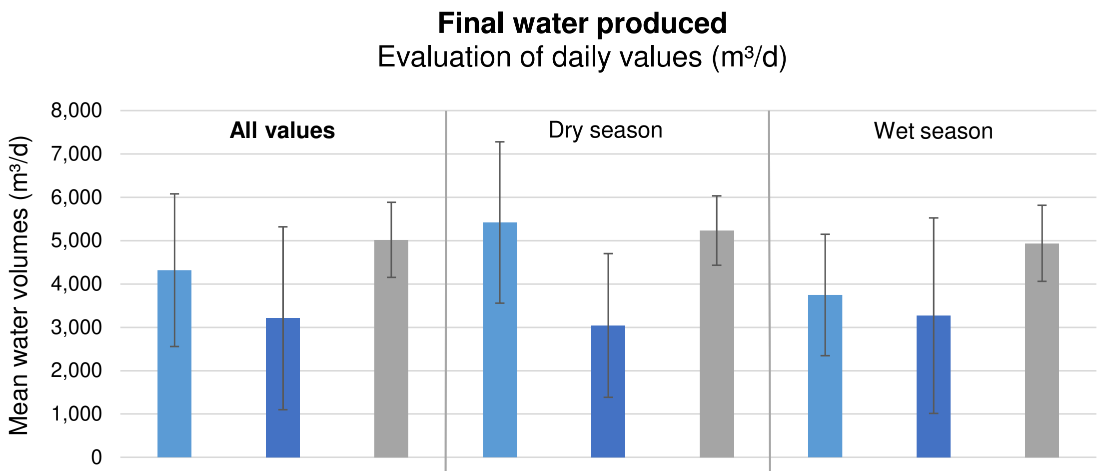
As Table 3 illustrated, the data availability for the three water volume parameters is generally better compared to the water quality parameters discussed in the previous chapter. While (1) apparent colour and (2) turbidity are missing or fragmented for large shares of the observation period at all three DWTPs, (3) raw water pumped, (4) final water produced, and (5) service water are generally available for more months and comparatively continuous. The only exception is service water at Sono, for which no single value exists. Therefore, no statements on service water volumes can be made for this DWTP, and hence no estimation of backwashing water uses. Large parts of the time series of (3) raw water pumped at the DWTPs of Sono and Malaba-Tororo and of (4) final water produced at the DWTP of Lirima had to be estimated using a conversion factor. This was performed either by NWSC or by the author (see Appendix B). The estimated values constitute no independent series of measurements but must be treated as approximations, potentially deviating from the real conditions at the DWTPs.

According to the respective plant overseers, Lirima processes approximately 1,200 m^3 of water per day and Sono approximately 3,500 m^3 per day. For Malaba-Tororo, John Ogire mentions a design capacity of 7,300 m^3/d, but de facto water volumes of approximately 5,700 m^3/d. As Figure 24 shows, the numbers for Sono and Malaba-Tororo can be confirmed by the quantitative data set but differ substantially for Lirima. The figure shows mean volumes of raw water pumped as well as related statistical parameters for the DWTPs of Lirima, Sono, and Malaba-Tororo. Figure 25 provides a similar evaluation for final water produced.



	All values: Lirima	All values: Sono	All values: Malaba-Tororo	Dry season: Lirima	Dry season: Sono	Dry season: Malaba-Tororo	Wet season: Lirima	Wet season: Sono	Wet season: Malaba-Tororo
Mean	4,770.14	3,369.70	5,714.22	5,903.74	3,195.62	5,905.32	4,180.41	3,433.97	5,644.33
SD	1,927.18	2,215.99	957.59	2,035.98	1,742.20	859.76	1,575.38	2,366.11	982.20
Min	0	0	570	1,500	74	1,402	0	0	570
Max	11,603	10,742	8,549	11,603	10,742	8,549	9,678	9,702	7,675
Median	4,668	3,518	5,870	5,998	3,423	6,052	4,209	3,565	5,791
n (-)	526	471	1,124	180	127	301	346	344	823

Figure 24: Statistical evaluation of all available daily values for raw water pumped at the DWTPs of Lirima, Sono, and Malaba-Tororo. Data provided by NWSC in hard copy form.



	All values: Lirima	All values: Sono	All values: Malaba-Tororo	Dry season: Lirima	Dry season: Sono	Dry season: Malaba-Tororo	Wet season: Lirima	Wet season: Sono	Wet season: Malaba-Tororo
Mean	4,320.01	3,209.11	5,017.45	5,419.53	3,043.31	5,234.44	3,744.68	3,270.32	4,938.09
SD	1,761.73	2,110.50	867.15	1,859.30	1,659.28	798.47	1,400.69	2,253.47	878.11
Min	0	0	496	1,311	70	1,290	0	0	496
Max	11,982	10,230	7,440	11,982	10,230	7,440	8,420	9,240	6,680
Median	4,198	3,350	5,120	5,474	3,260	5,320	3,731	3,395	5,030
n (-)	524	471	1,124	180	127	301	344	344	823

Figure 25: Statistical evaluation of all available daily values for final water produced at the DWTPs of Lirima, Sono, and Malaba-Tororo. Data provided by NWSC in hard copy form.

As Figure 24 shows, the estimations by the plant overseers are close to the mean values calculated from the quantitative data base for Sono and Malaba-Tororo. For Sono, the stated value (3,500 m³ per day) is only 130.30 m³ per day smaller than the calculated mean value (3,369.70 m³ per day). The difference for Malaba-Tororo is even smaller, with only 14.22 m^3 per day of difference between the stated (5,700 m^3 per day) and the calculated value (5,714.22 m^3 per day). In contrast, the deviation for Lirima is larger: The calculated value (4,770.14 m^3 per day) is almost four times as high as the stated value (1,200 m^3 per day). As the figure shows, Malaba-Tororo generally pumps most raw water from its intake river, followed by Lirima and Sono. The same proportions can be observed for the dry and the wet seasons. The numbers for raw water pumped at Lirima and Malaba-Tororo are higher during the dry season and lower during the wet season compared to the overall mean. This might be due to increased water demands by different users in the respective supply areas during the dry season, when precipitation is decreased, and hence more water is required for agricultural irrigation and other uses. For Sono, this seasonal effect cannot be observed. Due to a generally unsteady operation of this DWTP during the observation period, these unexpected water volumes might be due to operational reasons, decoupled from seasonal variations, as will be discussed below. The latter can also be confirmed by the standard deviations. Sono is subject to a comparatively high standard deviation, indicating that daily raw water volumes are relatively dispersed and spread out. A similar effect can be observed for Lirima, particularly during the dry season. The standard deviation is smallest at Malaba-Tororo, speaking for a rather constant volume flow and processes without extreme peaks or minima.

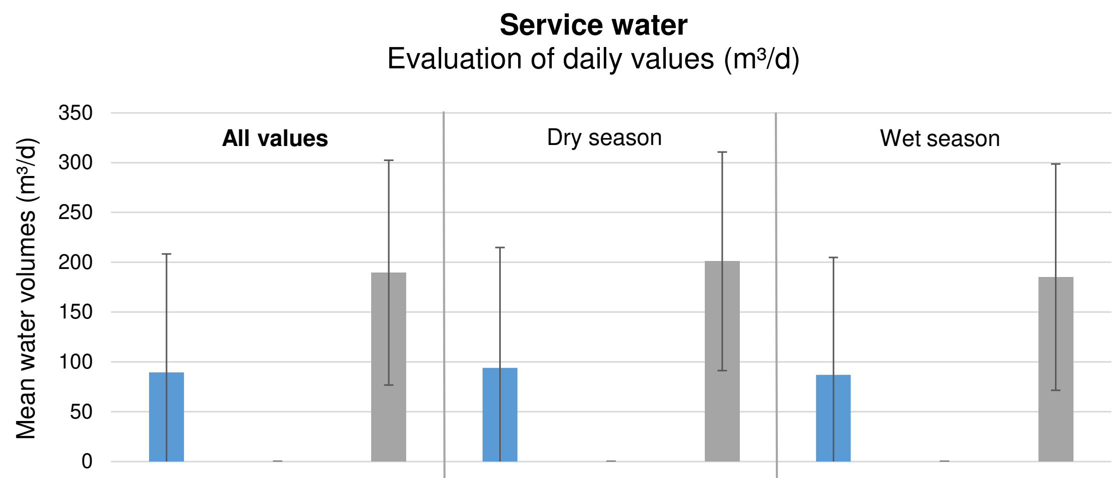
The general relationships observed at the case study DWTPs for raw water pumped can also be recognised for final water produced in Figure 25. An exception is the dry season, where more final water is produced in average at Lirima (5,419.53 m^3 per day) compared to Malaba-Tororo (5,234.44 m^3 per day). This is a surplus of 3.5 %. For all evaluated cases, the final water produced values are lower compared to the corresponding raw water pumped values, since different water uses, and losses occur onsite the respective DWTPs. These consist mainly of the service water volumes but go beyond that, i.e., the daily differences between raw water pumped and final water produced are regularly greater than the service water values.

According to the respective plant overseer, Lirima supplies approximately 50,000 people, Sono 45,000 people, and Malaba-Tororo 150,000 people, as mentioned in Chapter 4.1. Based on the final water produced values, these numbers are unexpected, since it implies that Lirima and Sono would produce similar final water volumes, while Malaba-Tororo produces about three times as much. This cannot be confirmed based on the quantitative data base. A simple control calculation shows that particularly the number for Sono results in a surprisingly high water supply rate per person. This might be associated with an overestimation of the processed water volumes, or an underestimation of the service population by the plant overseer. However, it is worth noting that the supplied areas and types of water consumers are specific for the three schemes, respectively. Lirima and Sono supply mainly rural areas where increased agricultural activity is expected, while Malaba-Tororo supplies also large urban settings. It is conceivable that for these and other reasons, the specific water consumption per person is higher at Sono compared to Lirima and Malaba-Tororo, which would explain the numbers indicated by the plant overseers.

Figure 26 shows mean volumes of service water as well as related statistical parameters for the DWTPs of Lirima and Malaba-Tororo. The higher general plant capacity of Malaba-Tororo can be recognised in the service water volumes as well. Malaba-Tororo uses more than twice as much service water per day as Lirima. At Lirima, the mean service water of 89.42 m^3 per day makes up a share of about 1.87 % of the daily raw water pumped at the plant. At Malaba-Tororo, the service water value of 189.59 m^3 per day makes up a share of 3.32 % of the daily raw water. These numbers illustrate that more service water is used at Malaba-Tororo compared to Lirima, in both absolute and relative terms. This implies that the various uses of service water, including backwashing of sand filters, flushing of sanitation facilities, cleaning of the yards, and laboratory uses, require more water at Malaba-Tororo compared to Lirima.

Since flushing of sanitation facilities, cleaning of the yards, and laboratory uses require comparatively low water volumes, it appears reasonable at first glance that higher service water volumes are related to higher backwash water requirements at Malaba-Tororo. However, these would be identifiable in the seasonal evaluations as well, including higher service water volumes in the wet season (due to elevated mean raw water turbidity) compared to the dry season. As Figure 26 illustrates, this cannot be observed in the data. On the contrary, service water volumes at both plants are higher in the dry compared to the wet season. Hence, the expectations with regards to higher average backwash water volumes during the wet season and lower during the dry season (see Chapter 1.3) cannot be confirmed based on the quantitative data base. An explanation for the observed values might be in an increased service water use for watering of the lawns during the dry season. As the DWTP of Malaba-Tororo has a considerably larger property area compared to Lirima, this might explain the differences between the plants and fits to the observed seasonal pattern.

As Figure 24 and Figure 25 indicated, peak water volumes per day during the observation period were higher at the DWTP of Lirima compared to Sono and Malaba-Tororo. The overall maximum values for raw water of 11,603 m^3 and for final water of 11,982 m^3 occurred on the same day, namely on 28^{th} January 2017, at Lirima. On this day, the final water value is higher than the raw water value. This can be explained by the storage capacity of a plant, i.e., water that was pumped into the DWTP in previous days is stored in different treatment facilities (e.g., sedimentation tanks, clear water well) and is then released at a specific day at a greater volume flow than is inflowing into the plant. The maximum values for Sono occurred on 27th December 2019, namely 10,742 m³ for raw water pumped (value estimated based on conversion factor), and 10,230 m³ for final water produced. In comparison, the maximum values at Malaba-Tororo were considerably lower, with 8,549 m³ of raw water and 7,440 m³ of final water on 15th December 2017. At all three DWTPS, the peaks occur during the dry season.



	Lirima	Sono	Malaba-Tororo	Lirima	Sono	Malaba-Tororo	Lirima	Sono	Malaba-Tororo
Mean	89.42	-	189.59	94.04	-	200.98	87.02	-	185.13
SD	118.84	-	112.71	120.81	-	109.77	117.91	-	113.60
Min	0	-	0	0	-	20	0	-	0
Max	530	-	940	413	-	840	530	-	940
Median	0	-	170	0	-	180	0	-	160
n (-)	527	0	1,050	180	0	295	347	0	755

Figure 26: Statistical evaluation of all available daily values for service water at the DWTPs of Lirima, Sono, and Malaba-Tororo. Data provided by NWSC in hard copy form.

The box plot diagrams for raw water pumped, final water produced, and service water in Figure 27 show that these maximum values can be considered as outliers of the respective data series. In general, upward outliers occur at all case study DWTPs for every type of water volume, though most occur for service water at Malaba-Tororo. This is due to a comparatively small box of quartiles, suggesting a stable use of service water. The maximum service water value of 940 m³ is achieved here on 5th March 2017. For raw water pumped and final water produced, the box of quartiles is smallest for Malaba-Tororo as well, indicating the most stable data series. Sono shows the biggest box, i.e., the largest spread in data. For raw water pumped and final water produced, many more downward outliers are observed for Malaba-Tororo than upward outliers. This suggests that days with reduced supply occurred more frequently, e.g., due to specific failures or maintenance works. At Lirima and Sono, no downward outliers exist since the lower whiskers are at 0 m^3 per day.

Figure 28, Figure 29, and Figure 30 show the respective developments of raw water pumped, final water produced, and service water over time at the DWTPs of Lirima, Sono, and Malaba-Tororo. In general, the figures show that Malaba-Tororo provides the most consistent and stable data series for all three parameters. For each case, 37 monthly values are available for the observation period in the extended monthly data sets. For Lirima, the data availability for raw water and final water is comparable, with 33 and 32 monthly values, respectively. In terms of service water, only half as many monthly values were available for Lirima (n = 18) as for Malaba-Tororo, while no data was provided for Sono.

Regarding the temporal progression of the respective water volumes, the figures show comparatively stable and constant curves for Malaba-Tororo. For raw water pumped and final water produced, no distinguishable trends that would speak for a long-term increase or decrease in water volumes can be observed. Major peaks or clear minima cannot be observed for both parameters at Malaba-Tororo. In contrast, the monthly time series for Lirima and Sono are subject to comparatively irregular progressions, including distinct peaks and even supply outages. For example, monthly raw water maxima at Lirima occurred in January 2017 (6,533 m^3/d), December 2017 (7,117 m^3/d), and February 2018 (6,818 m^3/d). The latter maximum is immediately followed by two of the lowest values within the data series (1,233 m^3/d and 1,109 m^3/d). The lowest raw water abstraction at Lirima occurred in July 2018 with only 742 m^3/d, which makes up only about one tenth of the monthly maximum for this DWTP. For Sono, monthly raw water maxima occurred in August 2018 (5,977 m^3/d), December 2018 (2,842 m^3/d), and November 2019 (4,863 m^3/d). As mentioned in Chapter 4.1, Sono was affected by landslides and land movements in October 2018 and May 2019. Both events are reflected in the data. While the first event leads to clearly reduced water volumes in October 2018 and a supply outage in November 2018 (0.00 m^3/d of raw and final water), the second event reduced the water volumes for May 2019. After these months, respectively, the water volumes at Sono increase again, most likely due to successful repair and maintenance works at the DWTP and its pipe network.

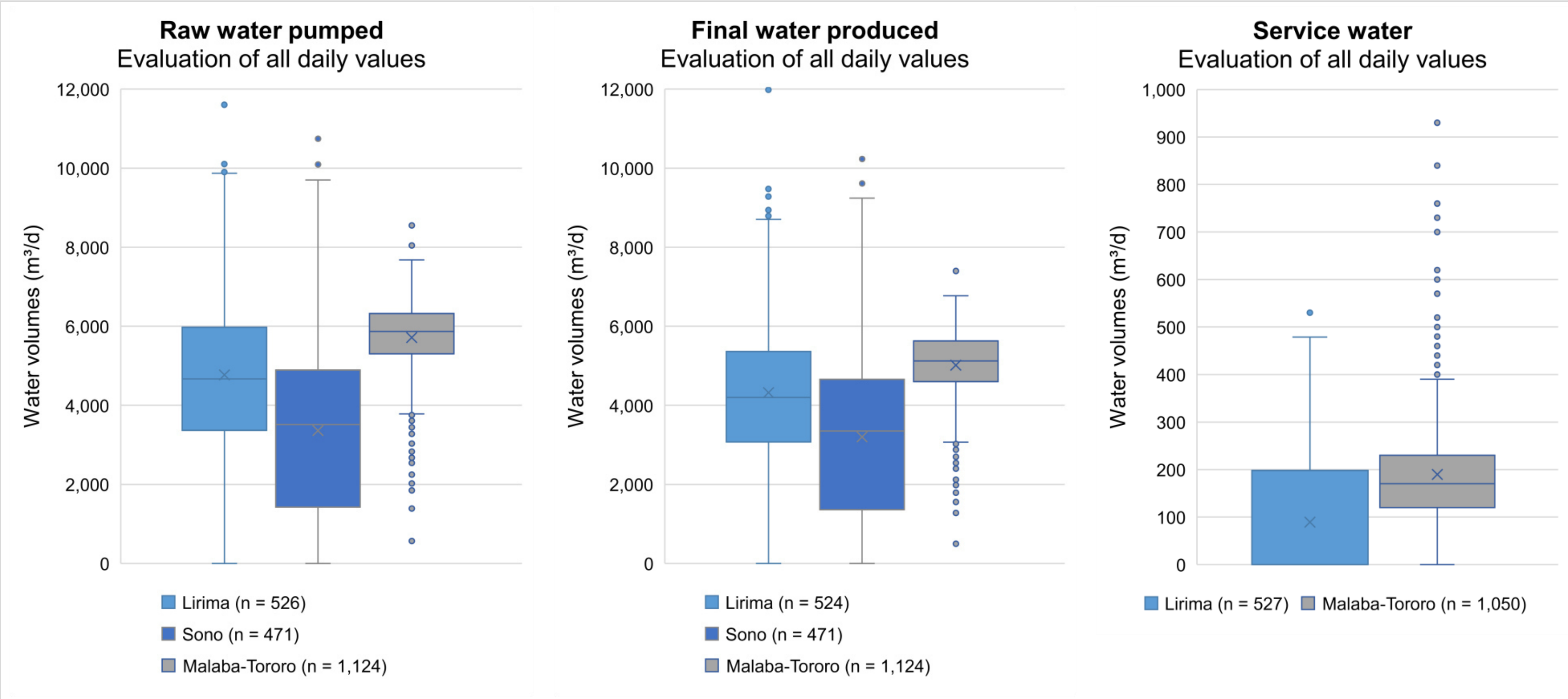


Figure 27: Box plot diagrams of all available daily values for raw water pumped, final water produced, and service water for Lirima, Sono, and Malaba-Tororo DWTPs (where applicable).

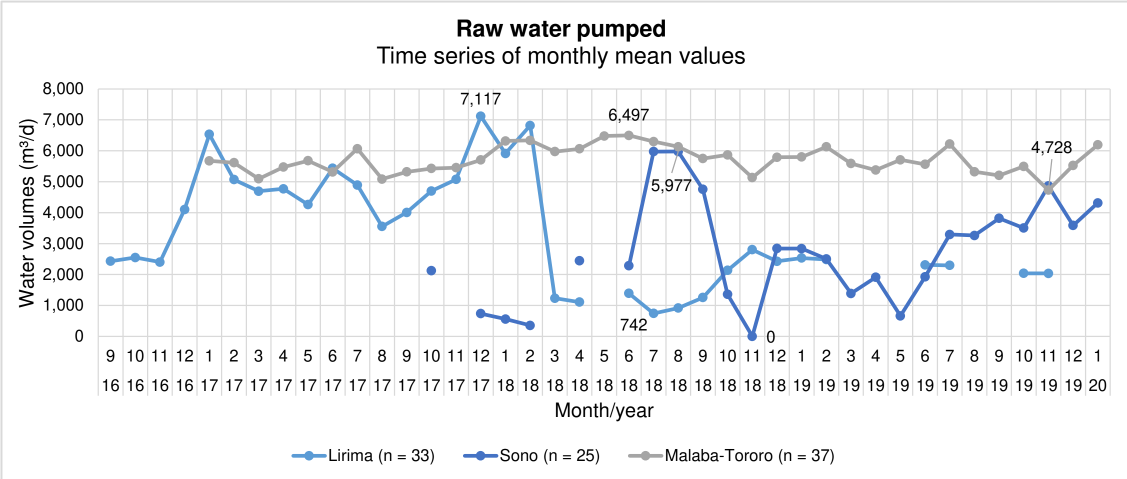


Figure 28: Time series diagram of monthly mean values for raw water pumped at the DWTPs of Lirima, Sono, and Malaba-Tororo, September 2016 to January 2020.

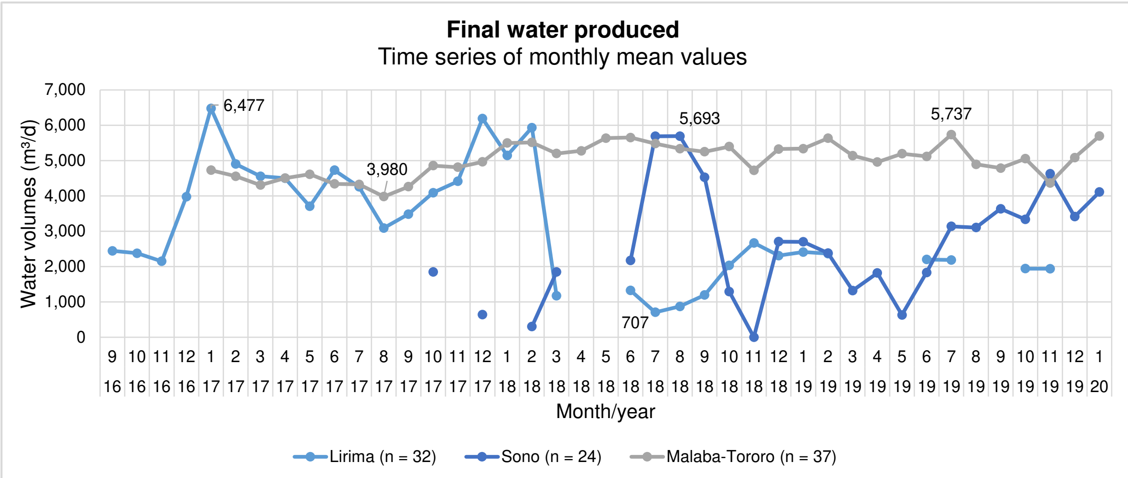


Figure 29: Time series diagram of monthly mean values for final water produced at the DWTPs of Lirima, Sono, and Malaba-Tororo, September 2016 to January 2020.

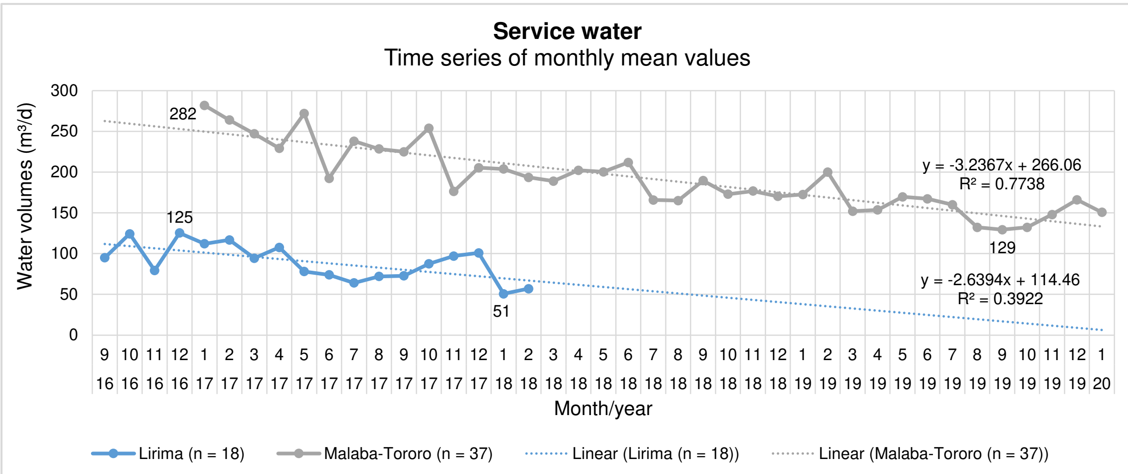


Figure 30: Time series diagram of monthly mean values for service water at the DWTPs of Lirima and Malaba-Tororo, September 2016 to January 2020. The trend lines for both time series are provided with their linear function equation and the corresponding coefficients of determination (R^2).

As Figure 30 shows, the monthly service water volumes for both Lirima and Malaba-Toro form comparatively stable and consistent curves. The time series contain some maxima and minima, which are though not as pronounced as discussed for the previous two diagrams. Yet, it appears that both data series show clear downward trends that speak for a long-term decrease in service water volumes. To illustrate those, linear trend lines were included for both monthly time series. Besides the information from the intercepts (114.46 m^3/d for Lirima and 266.06 m^3/d for Malaba-Tororo), which confirms the higher baseline service water use at Malaba-Tororo discussed before, the regression coefficients indicate that service water uses decreased with time at both DWTPs. At Lirima, the slope is at -2.64, which indicates that average service water use is in theory decreased by 2.64 m^3/d per month or 31.67 m^3/d per year. At Malaba-Tororo, the slope of -3.24 is even higher, resulting in a theoretical decrease in service water averages of 3.24 m^3/d per month or 38.84 m^3/d per year. The reliability of the forecast is better for the Malaba-Tororo trend line, as it shows a coefficient of determination of $R^2 = 0.77$ compared to $R^2 = 0.39$ for Lirima. The negative long-term trends for both data series may be due to more efficient service water uses and reductions in water losses at the DWTPs, for example through the installation of newer technologies or improved operational management.

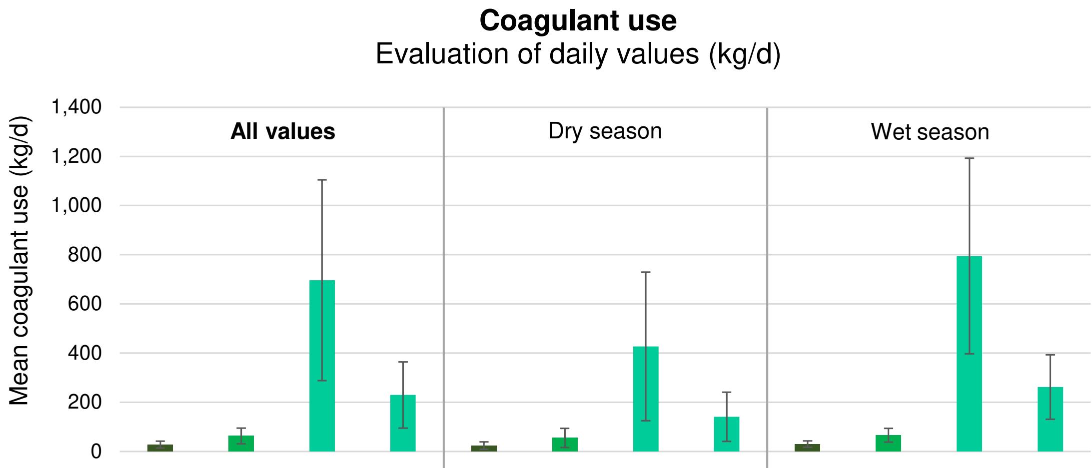
4.2.4. Coagulant chemicals

<u>Coagulant use</u>

As described in Chapter 4.1, alum (aluminium sulphate) is applied as coagulant chemical at the DWTPs of Lirima and Sono and ACH (aluminium chlorohydrate) at the DWTP of Malaba-Tororo. The coagulant doses at Lirima and Sono are set based on professional experience of the staff under consideration of the weather conditions, particularly with regards to precipitation. The doses are verified retrospectively with jar tests (see Table 2, record category v). Due to limited data availability and the fact that the jar tests do not directly influence the dose applied beforehand, the results were not further considered in this thesis. At Malaba-Tororo, the river basin characteristics allow the treatment plant staff to react to the weather conditions, i.e., to perform jar test experiments beforehand to determine and apply optimum coagulant doses. Therefore, it is expected that coagulant dosing at Malaba-Tororo is more precise and reacts better to the pollution in the stream water compared to Lirima and Sono.

For Lirima and Sono, the plant overseers report about dosing a comparatively constant or fix amount of alum to the raw water in dry conditions, which is adjusted during rainfall. According to Tito Amuku, approximately 20 kg of alum are used per dry day and 25 kg per rainy day at Lirima. Sarah Mbabazi reports about 50 kg to 150 kg alum used at Sono per day, depending on the weather conditions. Since coagulant dosing at Malaba-Tororo is determined from jar test experiments and is hence adjusted daily to the raw water quality, no estimate was provided by the plant overseer.

Figure 31 shows mean coagulant use as well as related statistical parameters for the DWTPs of Lirima, Sono, and Malaba-Tororo. For Malaba-Tororo, both the ACH use that was actually applied, and an estimated alum equivalent use based on the conversion factor of 0.33 (see Chapter 3.4.2) are provided. The latter is included to allow for a better comparison of coagulation at the three DWTPs. It is important to keep in mind that the alum equivalent value might be subject to under- or overestimation, as explained in Chapter 3.5. The figure illustrates that the use of coagulant chemicals increases from Lirima via Sono to Malaba-Tororo, i.e., increases the more downstream the DWTP is located within the SMMRB. While Lirima shows a mean alum use over all daily values of 27.75 kg/d, Sono's value of 62.90 kg/d is more than twice as much. At Malaba-Tororo, 229.96 kg/d of ACH are used, which equals to an estimated 696.04 kg/d of alum. This would be 25 times the value of Lirima, and 11 times the value of Sono. Even though alum and alum equivalent use should be compared with reservations, the quantitative difference between the upstream DWTPs and Malaba-Tororo is clearly pronounced. A similar impression can be retrieved from the evaluations for the dry season and the wet season. As expected, coagulant uses at all DWTPs are lower in the dry season and higher in the wet season compared to their overall averages. In each evaluation, Malaba-Tororo stands out as the DWTP with the highest coagulant use quantities, even before conversion of ACH to alum equivalent use. The highest relative difference between the case study DWTPs can be observed for the wet season between Lirima and Malaba-Tororo, where the factor between the two is at almost at 27.



	Lirima (alum)	Sono (alum)	Malaba-Tororo (alum eq.)	Malaba-Tororo (ACH)	Lirima (alum)	Sono (alum)	Malaba-Tororo (alum eq.)	Malaba-Tororo (ACH)	Lirima (alum)	Sono (alum)	Malaba-Tororo (alum eq.)	Malaba-Tororo (ACH)
Mean	27.75	62.90	696.04	229.69	23.79	54.96	427.00	140.91	29.83	65.87	794.68	262.25
SD	13.81	32.04	408.26	134.73	14.79	39.24	301.90	99.63	12.81	28.39	397.75	131.26
Min	2.50	12.50	51.52	17.00	8.33	15	51.52	17	2.50	12.50	145.45	48
Max	50	150	3,024.2	998.00	50.00	150	1,590.9	525	50	150	3,024.2	998.00
Median	25	50	621.21	205.00	20.83	30	309.09	102	25	50	751.52	248
n (-)	360	474	1,122	1,122	124	129	301	301	236	345	821	821

Figure 31: Statistical evaluation of all available daily values for coagulant use at the DWTPs of Lirima, Sono, and Malaba-Tororo. At Lirima and Sono, alum is used as coagulant chemical, while at Malaba-Tororo, ACH is used. To create alum equivalent (eq.) values for Malaba-Tororo, a conversion factor of 0.33 was used as described in Chapter 3.4.2. Original data provided by NWSC in hard copy form.

The standard deviations suggest that Lirima is the DWTP with the most stable data series, while the data series of Sono and Malaba-Tororo are more spread out. This impression can be confirmed by the box plot diagrams in Figure 32. As expected, the boxes between the lower and upper quartiles are comparatively narrow for Lirima, and wider for Sono and Malaba-Tororo. For Lirima, only one downward outlier value of 2.50 kg/d (dosed on four days between 31st August and 6th September 2017) and one upward outlier of 50 kg/d (dosed on 50 days within the time series) can be identified, which at the same time represent the minimum and maximum of the data series, respectively. Due to the comparatively broad box and the location of the resulting upper and lower whiskers for Sono, no outliers exist here. The minimum coagulant use of 12.50 kg/d was applied on three consecutive days in March 2019, while the maximum of 150 kg/d was applied on 17 days throughout the time series. For Malaba-Tororo, no downward outliers exist, but several upward outliers. The highest measured coagulant use of 994 kg (3,024 kg alum equivalent) occurred on 29th April 2019. Overall, the comparatively high number of upward outliers at Malaba-Tororo suggests a higher fluctuation in raw water quality compared to the other two DWPTs, and a high number of days where the DWTP had to react to impaired raw water qualities and particularly to turbidity peaks.

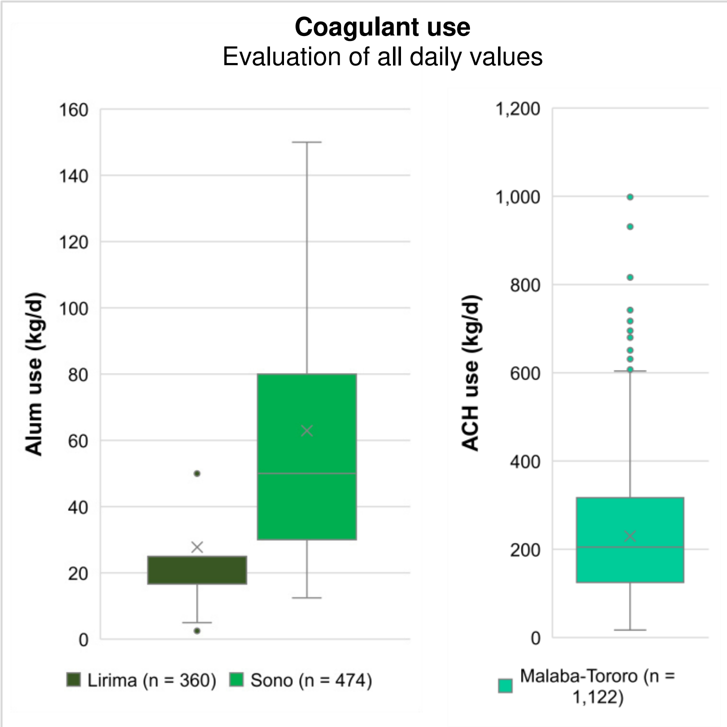


Figure 32: Box plot diagrams of all available daily values for coagulant use at Lirima, Sono, and Malaba-Tororo DWTPs. At Lirima and Sono, alum is used as coagulant chemical, while at Malaba-Tororo, ACH is used.

The described coagulant use maxima and minima can be identified in the time series diagram in Figure 33 as well. The diagram shows the development of daily coagulant use at the DWTPs of Lirima, Sono, and Malaba-Tororo over time. Besides illustrating frequent data gaps present for Sono and Lirima, the visualisation creates the impression that the daily values repeatedly follow straight horizontal lines, which implies equal daily alum use quantities. This impression can be confirmed by the quantitative data base. For example, at Lirima, 50 kg of alum were used on 88 days during the observation period (24 % of the data series), 25 kg on 173 days (48 %), and 16.67 kg on 39 days (11 %). This confirms the orders of magnitude mentioned by Tito Amuku, according to which approximately 20 kg of alum are used at Lirima per dry day and 25 kg per rainy day. A similar observation can be made for the DWTP of Sono, though the variety of applied alum quantities seems to be higher. 150 kg of alum were used on 17 days during the observation period (4 % of the data series), 100 kg on 90 days (19 %), 80 kg on 44 days (9 %), 75 kg on 68 days (14 %), 50 kg on 129 days (27 %), and 25 kg/d on 99 days (21 %) during the observation period. Except for the last alum use quantity, this goes in line with the statement of Sarah Mbabazi who reports about 50 kg to 150 kg alum used per day, depending on the weather conditions. Alum uses between 50 kg and 150 kg per day make up for 74 % of the data series, i.e., for 349 of a total of 474 days. Unlike for the raw water quality parameters (see Chapter 4.2.2), repeated values for coagulant uses at Lirima and Sono are not surprising. They are expected as they quantitatively confirm the approach for coagulant dosing described by the plant overseers of the two DWTPs.

In contrast to the rather rigid time series of Lirima and Sono which illustrate that specific alum quantities were applied repeatedly, the diagram for Malaba-Tororo shows fewer corners and edges and thereby appears more dynamic. Most values of the data series are unique which goes in line with the statement that they were determined based on jar test experiments. The result is a time series with clearly pronounced temporal variations and distinct yearly peaks in April/May. Besides the all-time high coagulant use mentioned before (994 kg of ACH on 29th April 2019), the other yearly peaks took place on 6th May 2017 (651 kg) and 16th April 2018 (430 kg). All coagulant use peaks can be observed during the wet season, in the vicinity of the first yearly precipitation peaks (see Chapter 4.2.1). The lowest coagulant use of 17 kg ACH was applied on 17th January 2017 in the middle of the dry season, as expected.

When shifting from daily to monthly resolution, the time series diagrams shown in Figure 34 are created. Here, the daily values from the previous time series are aggregated to monthly mean values to get a better overview of the temporal course of coagulant use at the case study DWTPs. After the extension of data as described in the methodology (see Chapter 3.4.2), further monthly data points are included in the diagrams for which daily values are missing. Examples are any values after February 2018 for Lirima, and before July 2018 for Sono. In general, Malaba-Tororo still shows the best data availability with 37 consecutive months without interruptions. However, the time series of Lirima and Sono were improved in comparison to the daily resolution, with 27 and 25 monthly values, respectively. Fortunately, the additional monthly values allow for a better comparison between Lirima and Sono, as now data for the same points in time are included.

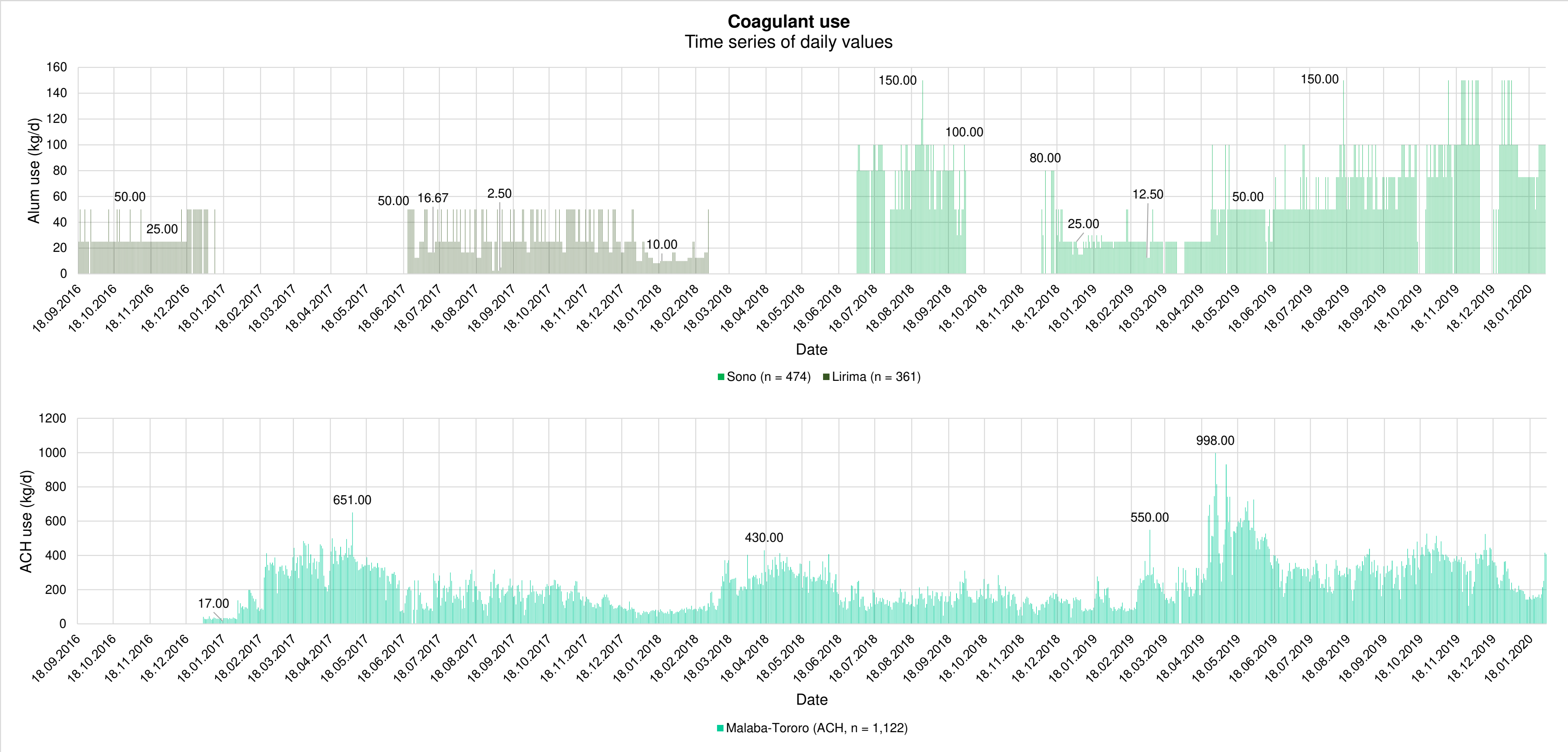


Figure 33: Time series diagrams of all daily values for alum use (Lirima, Sono) and ACH use (Malaba-Tororo), September 2016 to January 2020. .

Overall, the coagulant use relationships between the DWTPs as discussed for Figure 31 can be recognised in Figure 34 as well. At any time, the values are lowest at Lirima, higher at Sono, and highest at Malaba-Tororo, i.e., coagulant uses increase the more downstream the DWTP is located within the SMMRB. Furthermore, the monthly resolution allows to recognise the temporal progression of coagulant use at Sono better than with the daily resolution. While in the dry season months December to February comparatively low alum uses between 20 and 40 kg/d are predominant, considerably higher values occur in the wet season from March to November. An exception is the period from March 2019 to January 2020. On the one hand, comparatively small coagulant use averages of 24.52 kg/d and 31.48 kg/d were observed in the wet season months March and April, respectively. On the other hand, in the dry season months December 2019 and January 2020, high values of up to 111.11 kg/d are indicated. This creates the impression as if the time series had a delay of about two months, i.e., that if each value occurred two months earlier, it would better fulfil the expectations. At Malaba-Tororo, the yearly ACH use peaks occur in May 2017 (365.61 kg/d), April 2018 (299.47 kg/d), and, clearly pronounced, in May 2019 (568.94 kg/d). All these months are in the wet season. In the dry season, clearly smaller average ACH uses can be observed, for example in January 2017 (36.48 kg/d), January 2018 (69.13 kg/d), or February 2019 (121.68 kg/d). This fulfils the expectations better than the progression of Sono.

Even though the daily values were aggregated into monthly averages for the figure which smoothed out certain daily peaks and upward outliers, the differences of average ACH uses between the dry and the wet seasons are clear at Malaba-Tororo. For example, the month with the highest average ACH use, May 2019 (568.94 kg/d), is about 16 times as much as the lowest available value in January 2017 (36.48 kg/d). These margins are not as distinct for Sono and Lirima. At Sono, the highest average alum use in December 2019 (111.11 kg/d) is only about five times as much as the lowest value in January 2019 (23.39 kg/d). At Lirima, the highest average value from November 2017 (38.33 kg/d) is only about three times the value of January 2018 (12.26 kg/d). These numbers underline the expectations that coagulant use shows the highest temporal variability at Malaba-Tororo, less at Sono, and the least at Lirima.

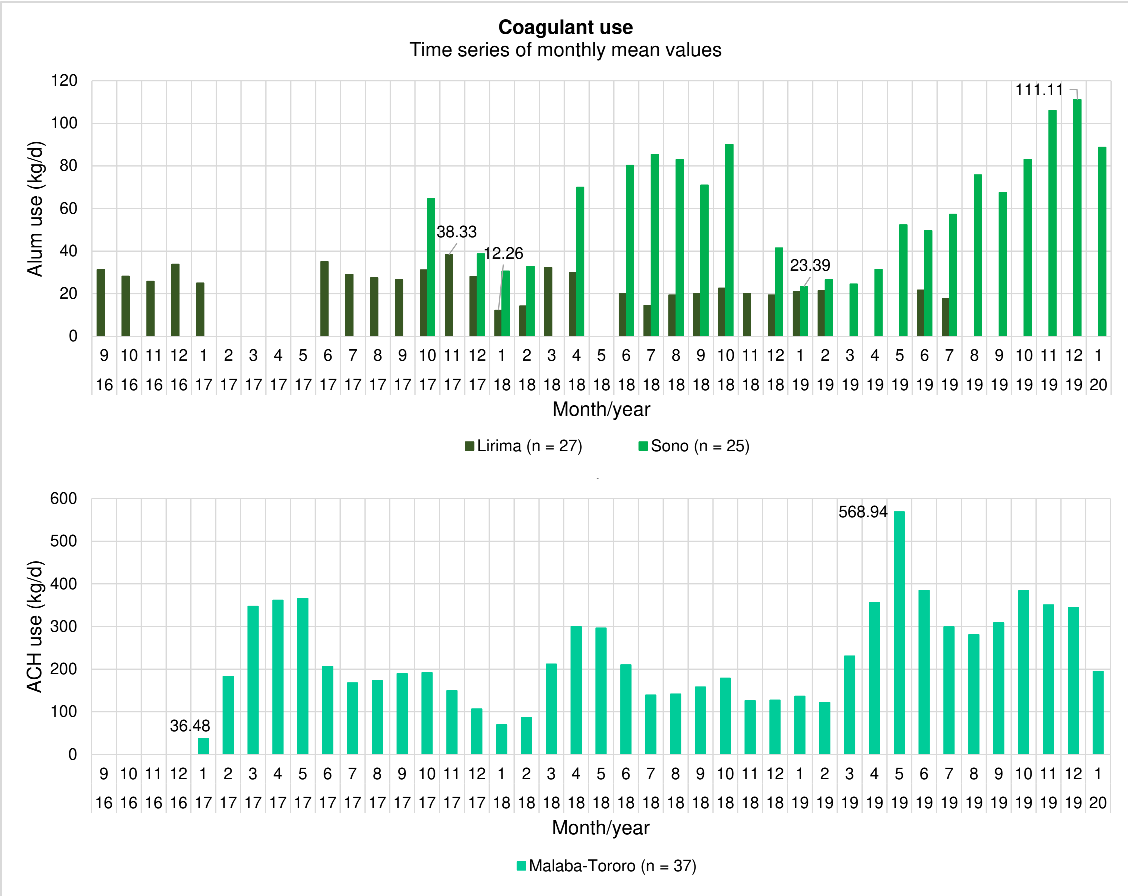
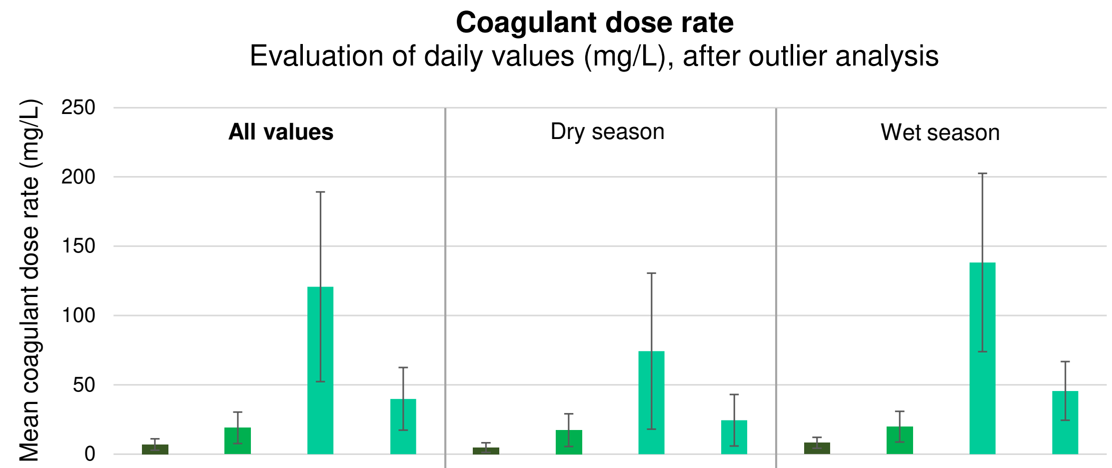


Figure 34: Time series diagrams of monthly mean values for alum use (Lirima, Sono) and ACH use (Malaba-Tororo), September 2016 to January 2020.

Coagulant dose rate

To put the coagulant use quantities just discussed in relation to the production activity at the case study DWTPs, daily coagulant dose rates were determined after Equation (1). The calculation relates the daily coagulant chemical uses with the corresponding daily raw water volumes. Figure 35 shows mean coagulant dose rates as well as related statistical parameters for the DWTPs of Lirima, Sono, and Malaba-Tororo, after outlier analysis. The outlier analysis removed 6 upward outliers for Lirima (upper limit for outliers: 19.72 mg alum/L), 65 upward outliers for Sono (upper limit for outliers: 63.13 mg alum/L), and 19 upward outliers for Malaba-Tororo (upper limit for outliers: 107.97 mg ACH/L). As was described for coagulant use, both the ACH that was de facto applied at Malaba-Tororo, and an estimated alum equivalent are included in the figure. The figure shows that mean coagulant dose rates increase from Lirima via Sono to Malaba-Tororo, i.e., increase the more downstream the DWTP is located within the SMMRB. This underlines the observations for coagulant use discussed before. While Lirima shows a mean alum dose rate of 7.00 mg alum/L, Sono's value of 19.03 mg alum/L is 2.7 times as much. At Malaba-Tororo, 39.85 mg ACH/L are used, which equals to an estimated 120.75 mg alum/L. This would be 17 times the value of Lirima, and six times the value of Sono. Even though alum and alum equivalent should be compared with reservations, the quantitative difference between the upstream DWTPs and Malaba-Tororo is clearly pronounced. For comparison: The average alum use in kg per day at Malaba-Tororo was 25 times the value of Lirima, and 11 times the value of Sono. As the numbers show, the differences between the two upstream DWTPs and Malaba-Tororo are less pronounced for the coagulant dose rates, i.e., the relationships are put into perspective when taking the different plant capacities into account. A similar impression can be retrieved from the evaluations for the dry and wet season. As expected, coagulant dose rates at all DWTPs are lower in the dry season and higher in the wet season compared to their respective overall averages. In every evaluation, Malaba-Tororo stands out as the DWTP with the highest coagulant dose rates, even before converting ACH to alum equivalent use. The highest relative difference between the DWTPs can be observed for the wet season between Lirima and Malaba-Tororo, where the factor between the two is at 5.5 when comparing alum to ACH, and at almost 17 when considering alum and alum equivalent. For comparison, the latter was at almost 27 for the relative coagulant use difference between Lirima and Malaba-Tororo in the wet season.



	Lirima (alum)	Sono (alum)	Malaba-Tororo (alum eq.)	Malaba-Tororo (ACH)	Lirima (alum)	Sono (alum)	Malaba-Tororo (alum eq.)	Malaba-Tororo (ACH)	Lirima (alum)	Sono (alum)	Malaba-Tororo (alum eq.)	Malaba-Tororo (ACH)
Mean	7.00	19.03	120.75	39.85	4.73	17.28	74.27	24.51	8.23	19.73	138.20	45.61
SD	4.11	11.33	68.43	22.58	3.51	11.77	56.27	18.57	3.89	11.09	64.34	21.23
Min	0.79	3.05	13.63	4.50	1.02	3.54	13.63	4.50	0.79	3.05	27.42	9.05
Max	19.69	63.05	319.94	105.58	16.32	58.00	301.03	99.34	19.69	63.05	319.94	105.58
Median	6.46	15.80	107.41	35.44	3.23	14.43	55.38	18.27	7.86	15.98	129.39	42.70
n (-)	353	388	1,103	1,103	124	111	301	301	229	277	802	802

Figure 35: Statistical evaluation of daily values for coagulant dose rate at the DWTPs of Lirima, Sono, and Malaba-Tororo, after outlier analysis. To create alum equivalent (eq.) values for Malaba-Tororo, the conversion factor of 0.33 was used as described in Chapter 3.4.2.

The standard deviations in Figure 35 suggest that Lirima is the DWTP with the most stable data series, while the ones of Sono and Malaba-Tororo contain more spread. In this context, it is important to note that the evaluation in the figure is presented after outlier analysis. If all values are included, the standard deviations are at 4.81 mg alum/L for Lirima, 447.34 mg alum/L for Sono, and 27.56 mg ACH/L for Malaba-Tororo. This shows that without outlier analysis, Lirima was the DWTP with the most stable data series as well, and that particularly at Sono, the outliers induce a large spread in the data series. To allow for a comparison of coagulant dose rates before and after outlier analysis, Figure 36 shows box plot diagrams for both cases. For the evaluation of all daily values shown on the left, the high number and magnitude of outliers at Sono limits the informative value of the diagram. Here, a total of 65 upward outliers exists, up to a calculated maximum value of 4,761.90 mg/L, i.e., almost five gram per litre. From the data series, it can be determined that these comparatively high values at Sono are primarily evoked by fluctuations of daily raw water volumes, as discussed in Chapter 4.2.3. Due to the shape of the applied equation, modest coagulant use quantities in combination with small raw water volumes result in high coagulant dose rates. For example, the highest coagulant dose rates at Sono were calculated for days with a coagulant amount of 50 kg which was regularly applied in the data series. At the same time, raw water volumes were at only 10.5 m^3 and 11 m^3, resulting in 4,545.45 mg alum/L and 4,761.90 mg alum/L, respectively. Consequently, each day within the data series with raw water volumes below 30 m^3 shows coagulant dose rates of 1,000 mg alum/L or above. Based on the records from the DWTPs, it cannot be determined whether such high dose rates were de facto applied to the processed water, or if they are just included in the records but were not carried out in reality. In any case, by excluding the upward outliers during outlier analysis, the observed fluctuations in chemical dose rates and hence the spread in the data series are reduced. Downward outliers do not exist for the case study DWTPs, neither before nor after outlier analysis. The minimum and maximum values after outlier analysis were provided above in Figure 35.

Figure 37 shows the development of coagulant dose rates at the DWTPs of Lirima, Sono, and Malaba-Tororo over time. Here, the daily values discussed before were aggregated to monthly mean values to get a better overview of the temporal course at the case study DWTPs. By creating monthly averages, the outliers in the data series are smoothened out. Hence, no outlier analysis was performed for the data presented in the figure. Further monthly data points were included in the diagram by extension of the data series, as described in the methodology (see Chapter 3.4.2). This affects all values after February 2018 for Lirima and the value before July 2018 for Sono. As was observable for coagulant use in Figure 34, Malaba-Tororo still shows the best data availability with data for 37 consecutive months without interruption. For Lirima and Sono, fewer monthly values are provided as in the coagulant use time series, namely 25 and 19, respectively. The additional monthly values allow for a better comparison between Lirima and Sono, as now data for the same points in time are shown.

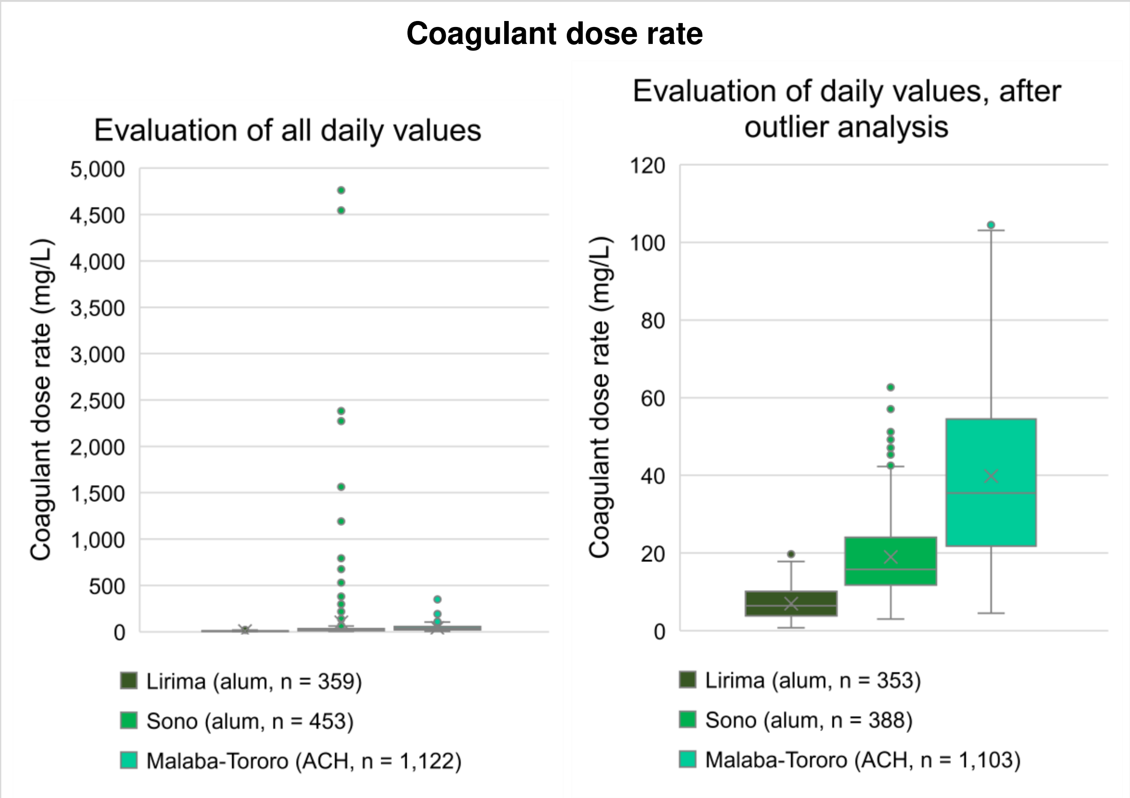


Figure 36: Box plot diagrams of calculated daily values for coagulant dose rate at Lirima, Sono, and Malaba-Tororo DWTPs, before and after outlier analysis. At Lirima and Sono, alum is used as coagulant chemical, while at Malaba-Tororo, ACH is used.

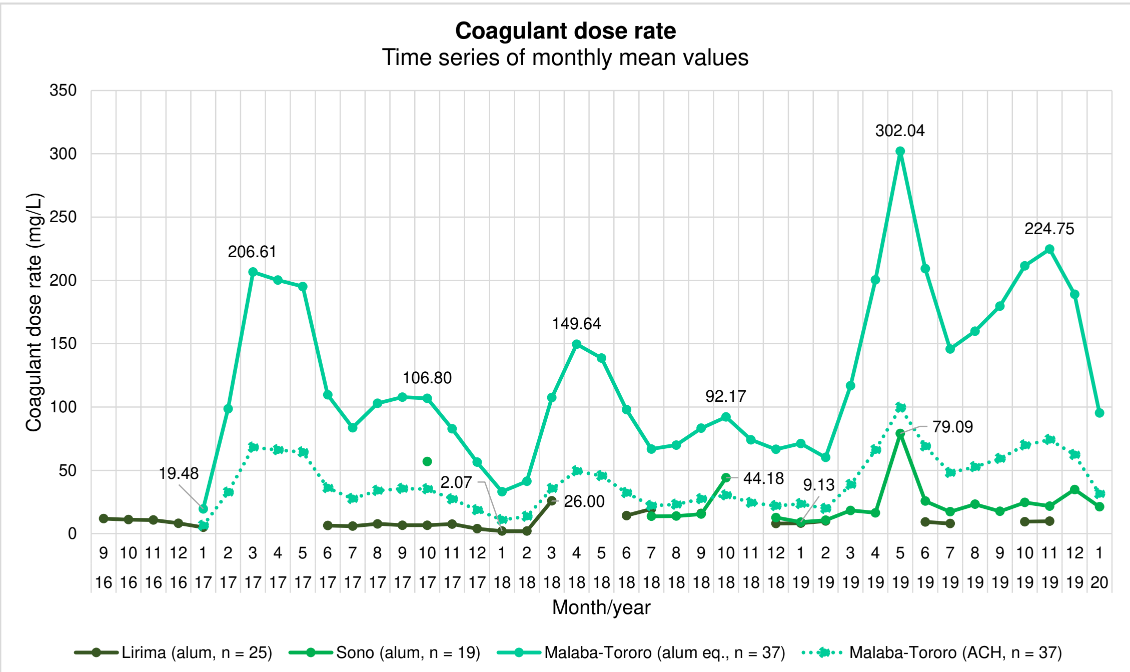


Figure 37: Time series diagram of monthly coagulant dose rates at the DWTPs of Lirima, Sono, and Malaba-Tororo, September 2016 to January 2020. At Lirima and Sono, alum is used as coagulant chemical, while at Malaba-Tororo, ACH is used. To create alum equivalent (eq.) values for Malaba-Tororo, the conversion factor of 0.33 was used as described in Chapter 3.4.2.

In the time series diagram in Figure 37, the basic relationships between the DWTPs as discussed for Figure 35 can be recognised again. In any month except for July 2018, the alum or alum equivalent values were lowest at Lirima, higher at Sono, and highest at Malaba-Tororo, i.e., coagulant dose rates increase the more downstream the DWTP is located within the SMMRB. This goes in line with the observations for coagulant use discussed before. In the diagram, it appears that the time series for Lirima is comparatively constant and includes only minor fluctuations in comparison to Sono and Malaba-Tororo. In fact, while the maximum monthly dose rate in March 2018 amounts to 26.00 mg alum/L, most other monthly dose rates are comparatively small. 18 out of 25 monthly values at Lirima are below 10 mg alum/L. In comparison, the time series for Sono includes higher values and a more recognisable curve. Only one value for January 2019 is below 10 mg alum/L, while 15 out of 19 monthly values are in the range between 10 and 30 mg alum/L. A clear peak can be observed in May 2019 with a dose rate of 79.09 mg alum/L. In this month, the time series of Malaba-Tororo has a distinct peak as well. While the ACH dose rate amounts to 99.67 mg/L, the converted alum equivalent dose rate is at 302.04 mg/L. Hence, the peak value of Malaba-Tororo is about 3.8 times the peak value of Sono.

In general, the time series of Malaba-Tororo shows the most recognisable development over time which seems to follow the seasonal variations. Besides the mentioned peak in May 2019, further maxima of the time series occurred in March and September 2017, April and October 2018, and November 2019. In every year, the first peak is considerably stronger than the second one. The differences between the first and second yearly peaks amount to 92 % in 2017, 62 % in 2018, and 34 % in 2019, i.e., showing a decreasing trend. At the same time, the values of both peaks in 2019 are greater than of any coagulant dose rate before within the observation period. Thus, it appears that 2019 was a year with comparatively high coagulant dosing at Malaba-Tororo. While all mentioned peak values occurred in the wet seasons, the dry season months show considerably lower values. All minima of the three time series considered occur in the dry season, namely in January 2018 at Lirima (2.07 mg alum/L), January 2019 at Sono (9.13 mg alum/L), and January 2017 at Malaba-Tororo (19.48 mg alum equivalent/L or 6.43 mg ACH/L). Even though daily peaks and upward outliers were smoothened out in the figure due to aggregation to monthly averages, the difference in coagulant dose rates between the dry and wet seasons at Malaba-Tororo are considerable. For example, the highest ACH dose rate in May 2019 (99.67 mg ACH/L) is about 16 times as much as the lowest available value in January 2017 (6.43 mg ACH/L). A similar picture is observed for Lirima, where the highest average value from March 2018 (26.00 mg alum/L) is about 13 times the value of January 2018 (2.07 mg alum/L). At Sono, the highest average alum dose rate in May 2019 (79.09 mg alum/L) is about nine times as much as the lowest value in January 2019 (9.13 mg alum/L). These numbers indicate that coagulant dose rates show the highest range of values at Malaba-Tororo, a smaller range at Lirima, and the smallest at Sono. Compared to the coagulant use quantities discussed before, the results indicate a considerably higher range of values for coagulant dose rates. Also, different to what is observed for coagulant dose rates, the range of monthly coagulant use values was the highest at Malaba-Tororo, smaller at Sono, and the smallest at Lirima.

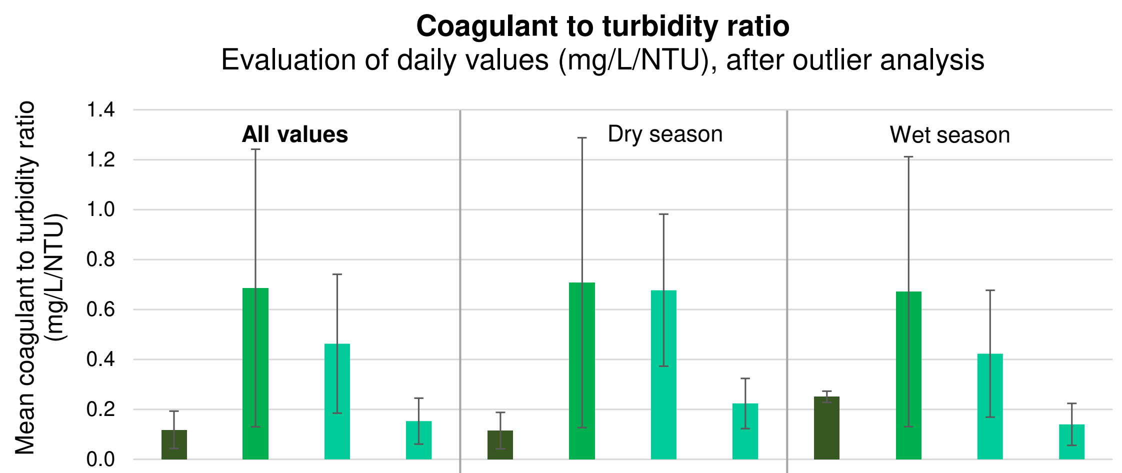
Comparison with the literature

For the Phong watershed in north-eastern Thailand, Sthiannopkao et al. (2007) reported of average turbidity values of 8.87 NTU in the dry season and 316 NTU in the wet season, and average alum doses varying between 28.46 mg/L in the dry season and 42.33 mg/L in the wet season. In comparison with the findings for the SMMRB, water quality in the Phong watershed varies more drastically between dry and wet season and shows rather low values in the dry season. In the present study, coagulant dose rates of 4.73 mg alum/L (Lirima), 17.28 mg alum/L (Sono), and 74.27 mg alum eq./L (Malaba-Tororo) were determined for the dry season. During the wet season, the dose rates increased to 8.23 mg alum/L (Lirima), 19.73 mg alum/L (Sono), and 138.20 mg alum eq./L (Malaba-Tororo). It can be observed that none of the case study DWTPs of the present research is similar to the dosing pattern indicated by Sthiannopkao et al. (2007). The DWTP of Sono is closest to the numbers from Thailand, though the changes between dry and wet season are not as pronounced. In this regard, the DWTP of Malaba-Tororo is closer to the empirical findings from the literature, indicating a factor of 1.86 between the two average values compared to a factor of 1.49 in the literature.

Coagulant to turbidity ratio

To put the coagulant dose rates just discussed in relation to the intake water quality at the case study DWTPs, daily coagulant to turbidity ratios were determined based on Equation (2). Due to the observations for raw water turbidity and coagulant dose rate presented in Chapter 4.2.2 and in the previous subsection, coagulant to turbidity ratios are expected to be roughly similar between the case study DWTPs. Mean raw water turbidities and mean coagulant dose rates increased from Lirima via Sono to Malaba-Tororo, i.e., increased the more downstream the DWTP is located within the SMMRB. Therefore, due to the shape of Equation (2), it is expected that the described observations for raw water turbidity and coagulant dose rate balance each other out to a certain extent and lead to comparable magnitudes for coagulant to turbidity at the case study DWTPs. Furthermore, it is expected that due to the different coagulant dosing strategies at the three DWTPs, the coagulant to turbidity ratio should show higher continuity and accuracy at Malaba-Tororo compared to Lirima and Sono, resulting in a lower standard deviation and less outliers for Malaba-Tororo. For Lirima and Sono, a larger spread of the parameter is expected. This is expected since dosing decisions at Lirima and Sono are mainly made based on professional experience of the plant overseers under consideration of the weather conditions, while at Malaba-Tororo, jar test experiments are performed to determine and apply optimum coagulant dose rates (see Chapter 4.1). Since jar test experiments deliver results under consideration of the sample water turbidity, it is expected that dosing decisions at Malaba-Tororo fit generally better to the raw water turbidity, resulting in a more consistent and stable coagulant to turbidity ratio for the DWTP.

Figure 38 shows mean coagulant to turbidity ratios as well as related statistical parameters for the DWTPs of Lirima, Sono, and Malaba-Tororo. As for coagulant dose rate, the values are provided after outlier analysis by which 6 upward outliers were excluded for Lirima (upper limit for outliers: 0.39 mg alum/L/NTU), 23 upward outliers for Sono (upper limit for outliers: 2.51 mg alum/L/NTU), and 23 upward outliers for Malaba-Tororo (upper limit for outliers: 0.43 mg ACH/L/NTU). As the coagulant to turbidity ratio combines values from three individual data series, namely coagulant use, raw water pumped, and raw water turbidity, each of the three influencing factors must be present at any given day to perform the calculation. Consequently, the numbers of values (n) of the coagulant to turbidity ratio are usually lower than for coagulant dose rate or raw water turbidity alone. Despite this fact, still 641 daily values are available for Malaba-Tororo and 197 for Sono. However, the data series of Lirima consists of only 81 daily values. This is mainly due to the limited availability of raw water turbidity at Lirima in 2016 and 2017 (see Table 3). Due to the temporal distribution of these 81 values, 79 are available during the dry season, while only two are available during the wet season. Therefore, the informative value of the coagulant to turbidity ratio for the wet season is low at Lirima and not representative of the true conditions.



	Lirima (alum)	Sono (alum)	Malaba-Tororo (alum eq.)	Malaba-Tororo (ACH)	Lirima (alum)	Sono (alum)	Malaba-Tororo (alum eq.)	Malaba-Tororo (ACH)	Lirima (alum)	Sono (alum)	Malaba-Tororo (alum eq.)	Malaba-Tororo (ACH)
Mean	0.12	0.69	0.46	0.15	0.11	0.71	0.68	0.22	0.25	0.67	0.42	0.14
SD	0.08	0.56	0.28	0.09	0.07	0.58	0.30	0.10	0.02	0.54	0.25	0.08
Min	0.03	0.10	0.02	0.01	0.03	0.12	0.15	0.05	0.23	0.10	0.02	0.01
Max	0.32	2.49	1.29	0.43	0.32	2.31	1.29	0.42	0.27	2.49	1.29	0.43
Median	0.10	0.43	0.43	0.14	0.09	0.40	0.66	0.22	0.25	0.46	0.39	0.13
n (-)	81	197	641	641	79	78	100	100	2	119	541	541

Figure 38: Statistical evaluation of daily values for coagulant to turbidity ratio at the DWTPs of Lirima, Sono, and Malaba-Tororo, after outlier analysis. To create alum equivalent (eq.) values for Malaba-Tororo, the conversion factor of 0.33 was used as described in Chapter 3.4.2.

The figure shows that the mean coagulant to turbidity ratio increases from Lirima via Malaba-Tororo to Sono. In every evaluation, Sono stands out as the DWTP with the highest coagulant dosing per raw water turbidity, even after converting ACH to alum equivalent values at Malaba-Tororo. This differs from the previous observations for the parameters coagulant use and coagulant dose rate discussed earlier in this chapter, for which the mean values increased from Lirima via Sono to Malaba-Tororo, i.e., increased the more downstream the DWTP is located within the SMMRB. The deviating observations might be due to elevated levels of raw water turbidity at Malaba-Tororo, thereby decreasing the mean coagulant to turbidity ratio at the DWTP, or comparatively small raw water turbidities at Sono, thereby increasing the ratio at this DWTP. Considering Figure 18, both explanations are conceivable, as well as a combination of both. At first glance, the mean coagulant to turbidity ratio does not show similar magnitudes, but distinct differences between the considered DWTPs and seasonal evaluations. However, the overall range of values is considerably smaller than ones of coagulant use and coagulant dose rate. All calculated mean values of coagulant to turbidity ratio are in a range between 0.11 mg alum/L/NTU and 0.71 mg alum/L/NTU, resulting in a factor of 6.5 between the lowest and highest value. In contrast, the factor between the lowest and highest mean coagulant use is at 33 (see Figure 31), while for coagulant dose rate, this factor is at 29 (see Figure 35). These numbers illustrate that the coagulant to turbidity data series is more uniform and shows a narrower range of values with more similar orders of magnitudes compared to the other two coagulation-related parameters, which fulfils the expectations described above.

The standard deviations shown in Figure 18 suggest that Lirima is the DWTP with the most stable data series, followed by Malaba-Tororo and Sono. Though the lowest value in the figure is not meaningful due to the limited number of observations for Lirima in the wet season (n = 2), the other two evaluations include the lowest values for Lirima as well. At first glance, this contradicts the expectation that the coagulant to turbidity ratio would show the highest continuity and accuracy at Malaba-Tororo. However, a number of observations put this impression into perspective. While Lirima's data series consists of only 81 daily values that originate almost entirely from the dry season (28th November 2017 to 28th February 2018), Malaba-Tororo provides about eight times as many daily observations with 641 values, originating from both the dry and the wet season (1st January 2017 to 30th November 2018). Furthermore, both raw water turbidities (see Figure 21) and coagulant uses (see Figure 33) are not stable at the DWTP, but subject to variations and fluctuation which cannot be observed to the same extent for Lirima. Against this background, the comparatively low standard deviations for the coagulant to turbidity ratio at Malaba-Tororo are noteworthy. The overall mean value of 0.09 mg ACH/L/NTU or 0.28 mg alum eq./L/NTU is only 3.5 times the value of Lirima. Thereby, the standard deviation of Malaba-Tororo is only half the value for Sono of 0.56 mg alum/L/NTU, for which the largest spread in the data series can be observed. This is underlined by the box plot diagram in Figure 39, which allows for a comparison of coagulant to turbidity ratios before and after outlier analysis. As observed before for coagulant dose rate, the high number and magnitude of outliers at Sono limits the informative value of the diagram. The 23 upward outliers include values of up to 71.02 mg alum/L/NTU, which is about 12 times more than the highest value observed for any other DWTP. As elaborated for coagulant dose rates, these very high values originate primarily from fluctuations of daily raw water volumes. By excluding the upward outliers as part of the outlier analysis, the observed fluctuations in coagulant to turbidity ratios and hence the spread in the data series are reduced. Yet, Sono remains the DWTP with the highest, even if excluding all 26 upward outliers. Downward outliers do not exist for any of the case study DWTPs, neither before nor after outlier analysis. The minimum and maximum values after outlier analysis were provided above in Figure 38.

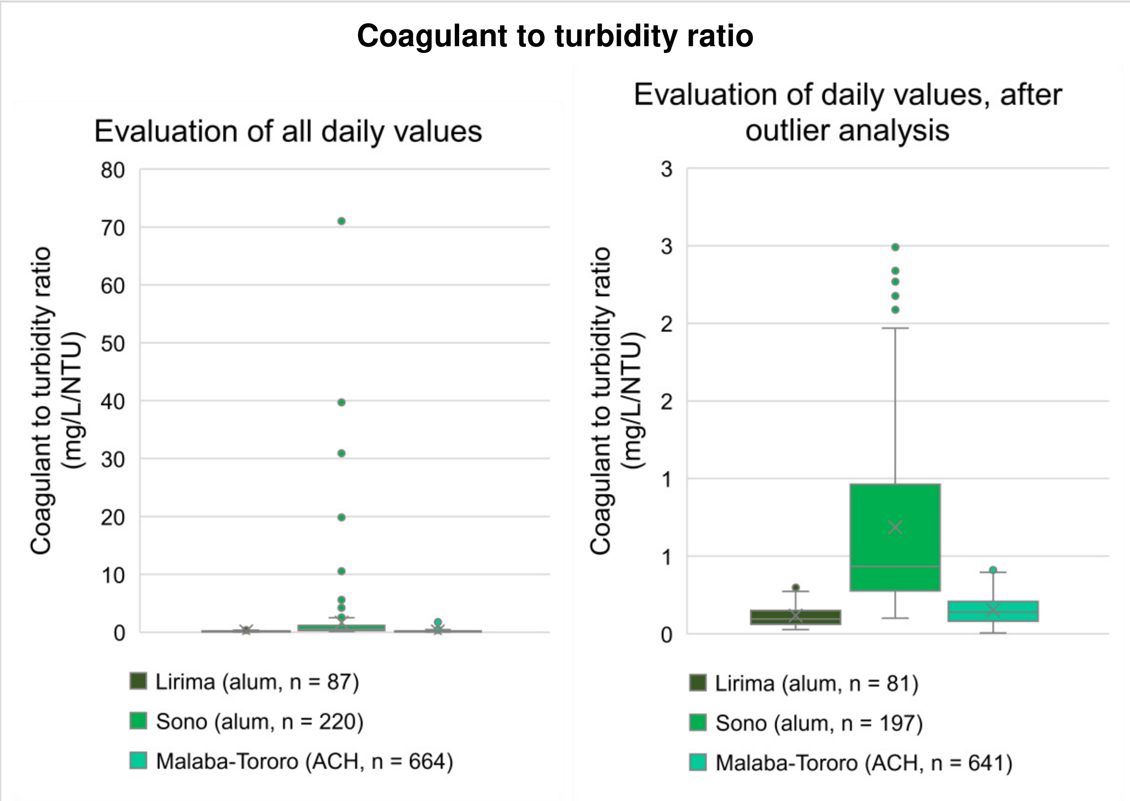


Figure 39: Box plot diagrams of calculated daily values for coagulant to turbidity ratio at Lirima, Sono, and Malaba-Tororo DWTPs, before and after outlier analysis. At Lirima and Sono, alum is used as coagulant chemical, while at Malaba-Tororo, ACH is used.

Figure 40 visualises several of the observation discussed above. The time series diagram shows the development of daily coagulant to turbidity ratios after outlier analysis for the DWTPs of Lirima, Sono, and Malaba-Tororo over time. The figure indicates that the period in which values for Lirima are provided is comparatively short and lies almost entirely in the dry season. In contrast, the data series for Sono and Malaba-Tororo include more data points and observations for both the dry and the wet periods. Further, it is visible that the coagulant to turbidity ratios generally increase from Lirima via Malaba-Tororo to Sono. For Sono, the largest spread in daily data can be recognised, with values between 0.10 mg alum/L/NTU on 3rd March 2019 and 2.49 mg alum/L/NTU on 10th October 2019. Both values were observed in the wet season. The minimum for Lirima of 0.03 mg alum/L/NTU occurs five times within the data series, while the peak value of 0.32 mg alum/L/NTU occurred on 23rd February 2018. At Malaba-Tororo, the minimum value occurred three times within the data series, namely on 2nd March, 12th May, and 3rd June 2018, while the maximum value of 1.29 mg alum eq./L/NTU occurred twice, on 12th January and 26th October 2018. As these dates indicate, the minimum and maximum values at the three DWTPs cannot be unambiguously allocated to either the dry or the wet season.

Upon closer inspection of the coagulant to turbidity ratio data series, two different explanatory approaches for changes and fluctuations in the values can be observed. Firstly, they can be due to fluctuating raw water volumes. This occurs predominantly at Sono. As an example, the peak value of 2.49 mg alum/L/NTU occurs on a day with 2,510 m^3 of raw water pumped and a raw water turbidity of 20 NTU. On the subsequent day, the coagulant to turbidity ratio changes to 0.82 mg alum/L/NTU, a value only one third of the previous day. This occurs though the raw water turbidity stayed nearly constant with then 16 NTU. At the same time, the volume of raw water pumped almost doubled to 4,568 m^3, which explains the decrease in coagulant to turbidity ratio. Secondly, fluctuations in coagulant to turbidity ratio can be due to variations in raw water quality. This occurs predominantly at Malaba-Tororo. As an example, the peak value of 1.29 mg alum eq./L/NTU occurs on a day with 5,228 m^3 of raw water pumped and a raw water turbidity of 58 NTU. Two days later, the coagulant to turbidity ratio is at 0.11 mg alum eq./L/NTU, a value less than one tenth of the value from two days ago. Yet, the raw water pumped increased only moderately with then 5,913 m^3. But at the same time, raw water turbidity increased considerably to 600 NTU, which explains the decrease in coagulant to turbidity ratio. At Lirima, none of the two explanatory approaches can be observed this pronounced, and the values are generally more uniform. From the observations, it can be derived that at Sono, the consistency and continuity of coagulant dosing is mainly disturbed by irregular operations of the treatment plant with regards to fluctuating water volumes, while at Malaba-Tororo, stream water quality fluctuations are the main challenge for a consistent and accurate coagulant dosing.

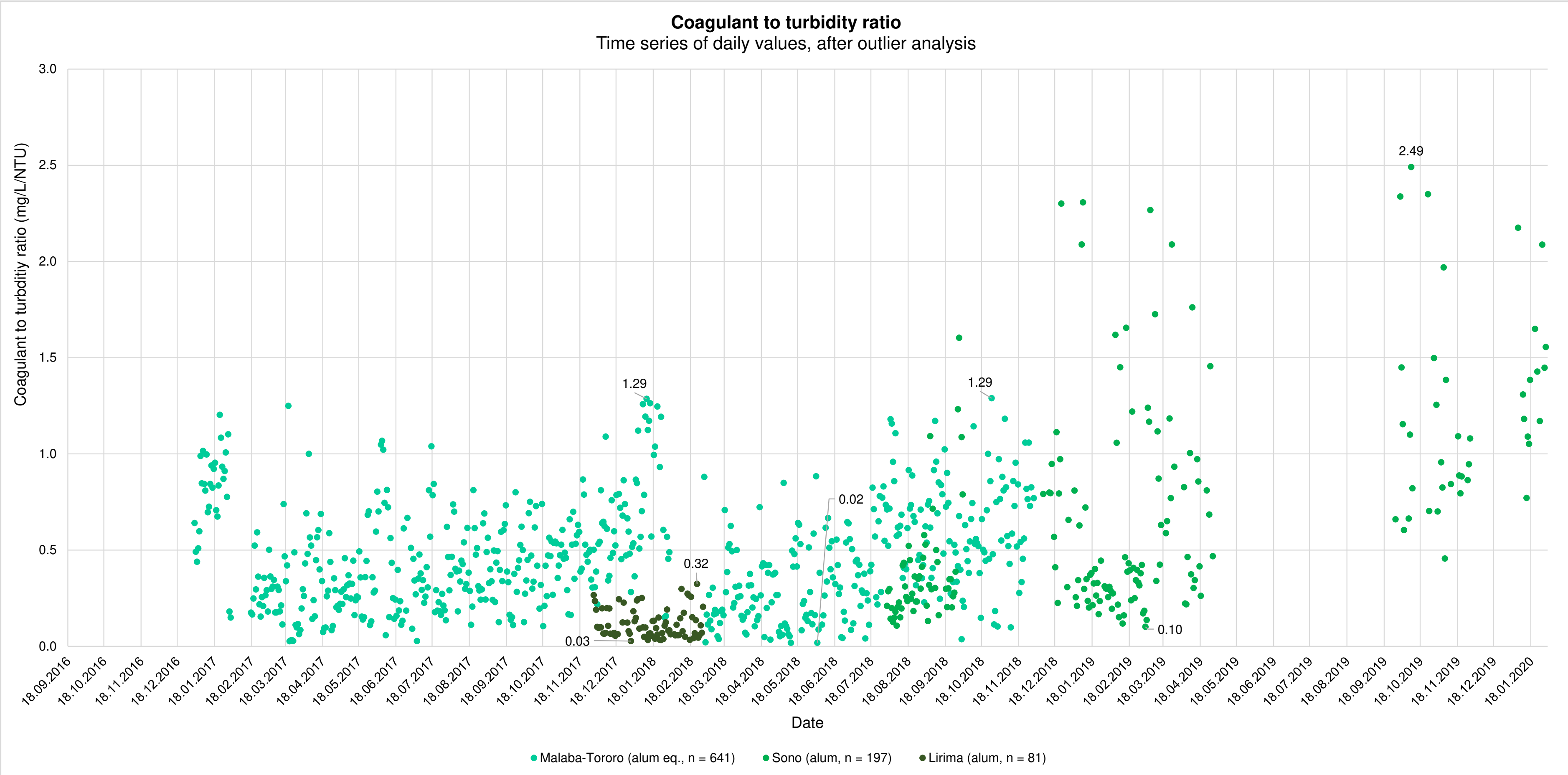


Figure 40: Time series diagrams of daily values for coagulant to turbidity ratio at the DWTPs of Lirima, Sono, and Malaba-Tororo, December 2016 to January 2020, after outlier analysis. To create alum equivalent (eq.) values for Malaba-Tororo, the conversion factor of 0.33 was used as described in Chapter 3.4.2.

4.3. Simple regression analyses

As described in Chapter 4.1, the experience of NWSC staff is that increased precipitation during the wet seasons is associated with higher sediment and particle contents in the intake water of DWTPs, particularly at plants located more downstream within the SMMRB. Furthermore, increased levels of those substances in the intake water leads to increased use of coagulant chemicals at the DWTPs, besides other effects. To be able to better retrace these statements and to allow for a visual impression of the described relationships, Figure 41, Figure 42, and Figure 43 illustrate merged monthly time series diagrams for the selected combinations of parameters. Figure 41 shows monthly precipitation sums and monthly mean raw water turbidity; Figure 42 illustrates monthly precipitation sums and monthly mean coagulant dose rates; and Figure 43 provides monthly mean raw water turbidity and monthly mean coagulant dose rates. For each combination of parameters, the diagrams show the times series of all case study DWTPs, as presented and discussed in Chapter 4.2.

The three figures illustrate that Malaba-Tororo shows the most pronounced temporal progressions for the each of the evaluated relationships. It appears that in general, both raw water turbidity and coagulant dose rate at the DWTP follow the seasonal course indicated by precipitation. For example, in the dry season months December to February, values for both parameters are comparatively small, which can be observed with regards to low turbidity values around the minimum in February 2018, or low coagulant dose rates in the vicinity of the minima in January 2017, January 2018, and February 2019. At the other end of the scale, peaks of the parameters occur frequently in the same months as precipitation peaks. This is visible for the raw water turbidity peak in May 2019, and the coagulant dose rate peaks in April 2018, October 2018, and May 2019. Even though there are also some deviations from these observations, for example in March 2017, the figures confirm that there must be a certain degree of proportional correlation between precipitation and raw water turbidity, as well as between precipitation and coagulant dose rate at Malaba-Tororo.

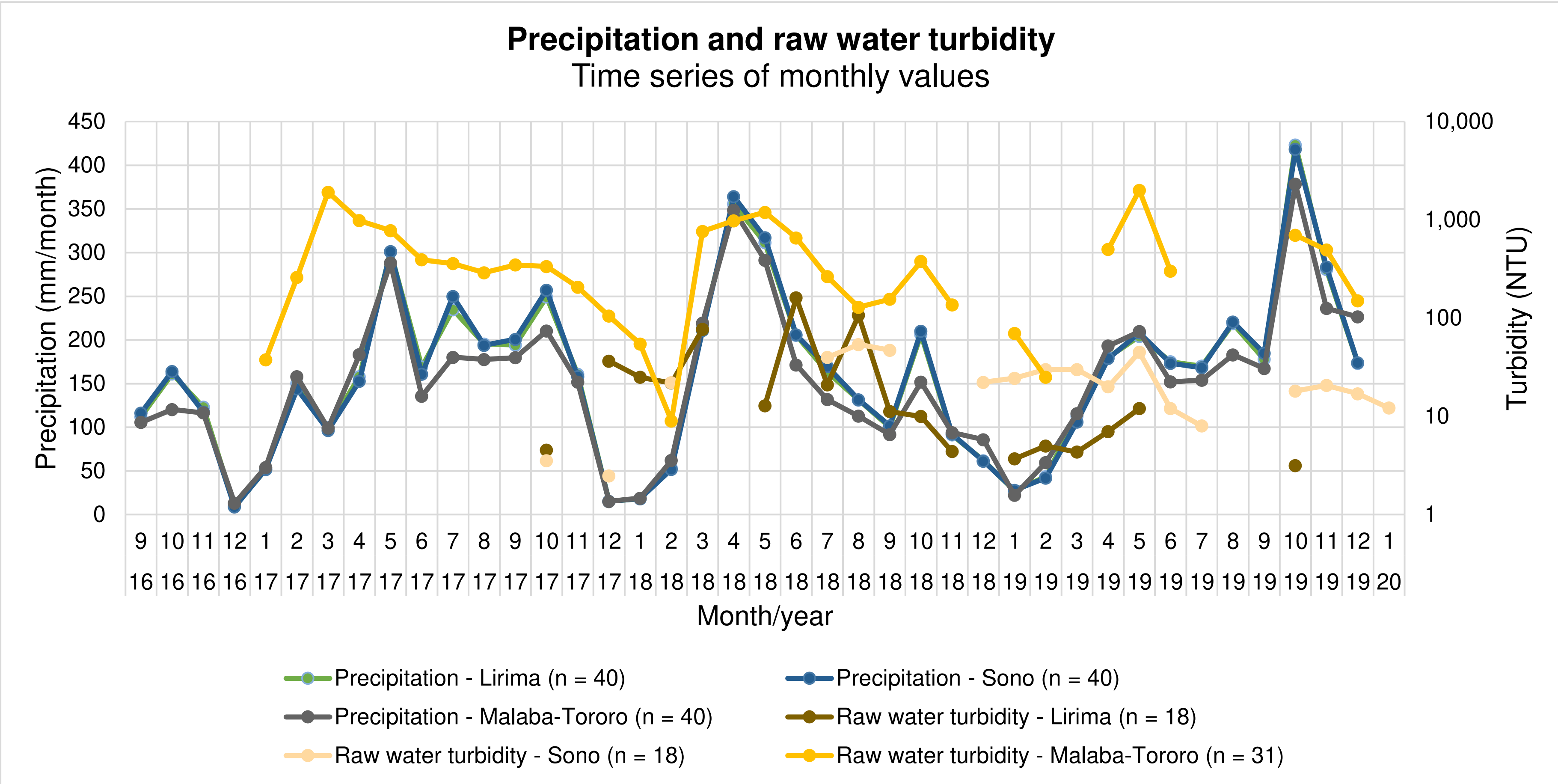


Figure 41: Time series diagram of monthly sum values for precipitation in the relevant upstream areas, as well as mean values for raw water turbidity at the intakes of Lirima, Sono, and Malaba-Tororo DWTPs, September 2016 to January 2020.

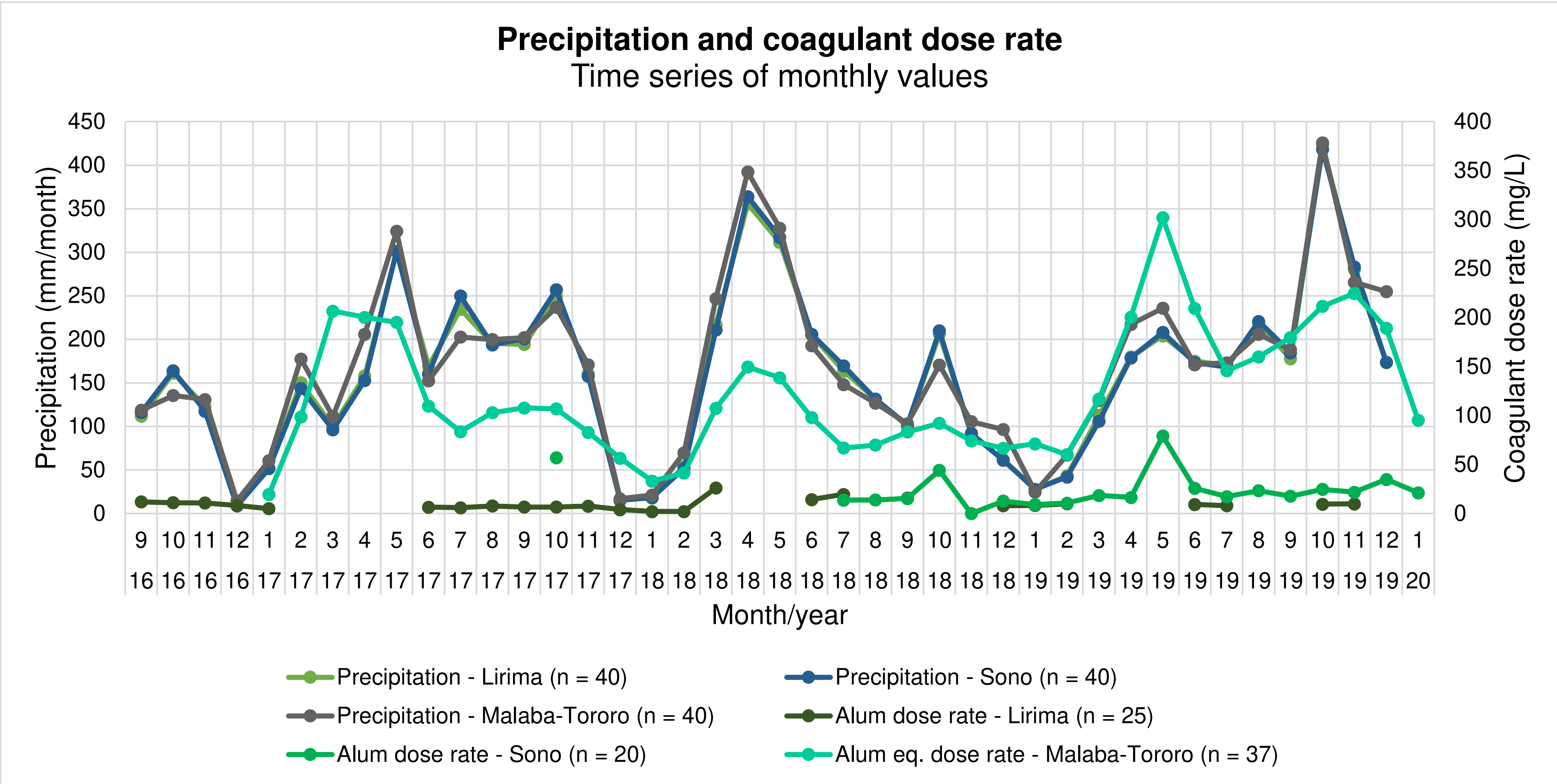


Figure 42: Time series diagram of monthly sum values for precipitation in the relevant upstream areas, as well as mean values for coagulant dose rate at the DWTPs of Lirima, Sono, and Malaba-Tororo, September 2016 to January 2020. At Lirima and Sono, alum is used as coagulant chemical, while at Malaba-Tororo, ACH is used. To create alum equivalent (eq.) values for Malaba-Tororo, the conversion factor of 0.33 was used as described in Chapter 3.4.2.

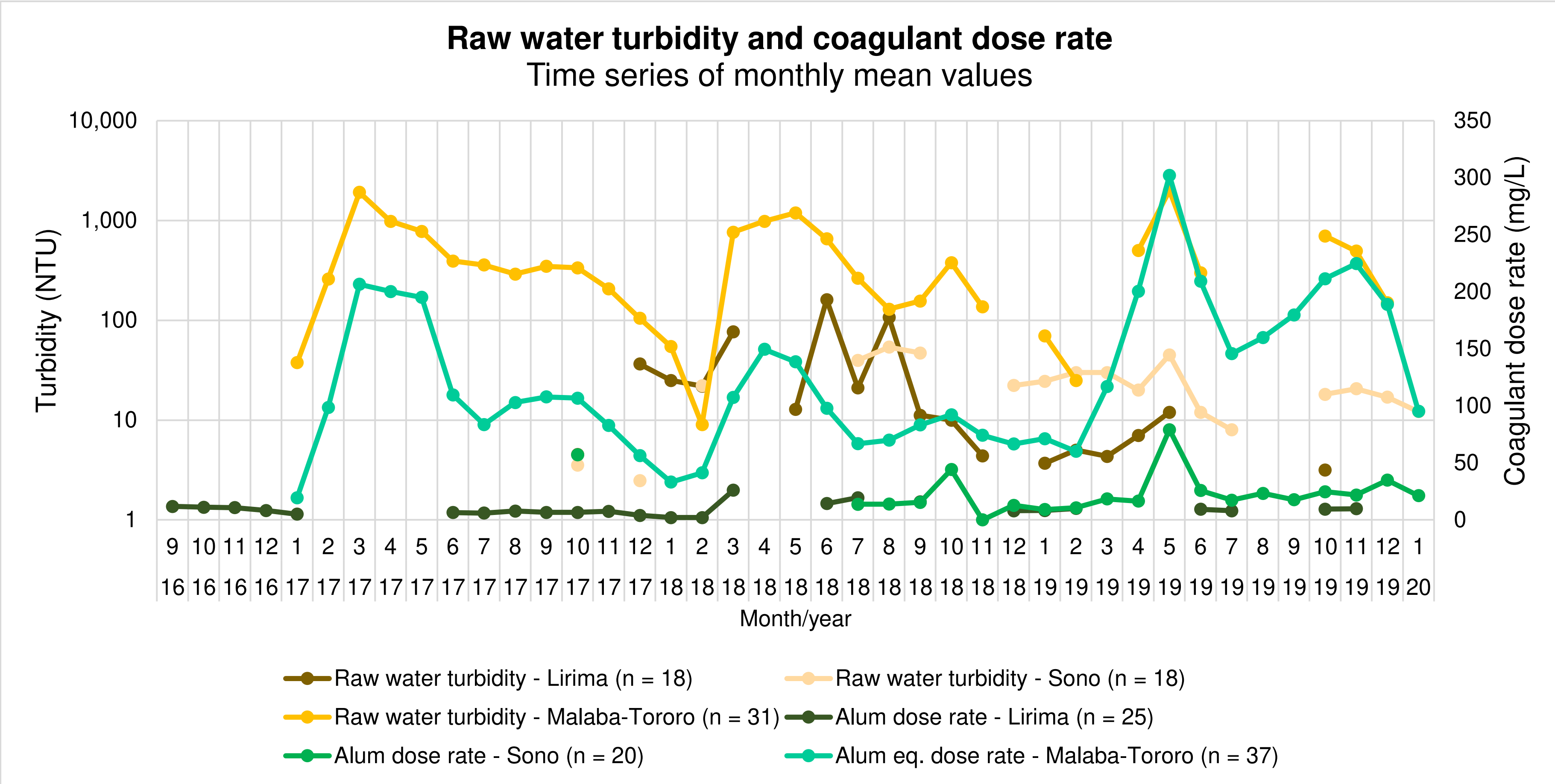


Figure 43: Time series diagram of monthly mean values for raw water turbidity and coagulant dose rate at the DWTPs of Lirima, Sono, and Malaba-Tororo, September 2016 to January 2020. At Lirima and Sono, alum is used as coagulant chemical, while at Malaba-Tororo, ACH is used. To create alum equivalent (eq.) values for Malaba-Tororo, the conversion factor of 0.33 was used as described in Chapter 3.4.2.

For Lirima and Sono, the observations are not as clear. Due to a generally lower availability of monthly data for the two DWTPs, it is more difficult to evaluate and compare the temporal progressions of the respective parameters in the diagrams. In some instances, monthly peaks are observed as expected in parallel to precipitation. Examples are the maxima of raw water turbidity at both DWTPs in May 2019, or of coagulant dose rate at Sono in October 2018 and May 2019. Yet, these peaks are less pronounced as at Malaba-Tororo. At Lirima, the temporal progression of raw water turbidity from December 2017 to March 2018 roughly fits the precipitation curve. Unfortunately, the progression cannot be evaluated for the subsequent months due to data gaps and fluctuating values from April to August 2018. From September 2018 to May 2019, the monthly turbidity values seem to fulfil the expectations again, though another data gap in December 2018 limits this observation.

Regarding coagulant dose rates, Lirima does not show a visible progression in parallel to precipitation, which is most likely due to a generally small range of values and frequent data gaps. At Sono, the monthly values for raw water turbidity do largely not match the expectations from the precipitation curve. For example, in the dry season months December 2018 to February 2019, comparatively low turbidity values are expected. However, the raw water turbidities stay rather constant in a range between 22.25 NTU in December and 30.00 NTU in February. A clear minimum, as for precipitation in January 2019, cannot be identified. Also, the all-time precipitation high in October 2019 does not seem to influence raw water turbidity at Sono much. The mean turbidity value for this month of 18.14 NTU is even smaller than any observation during the previous dry season at the plant. From April to July 2019, the turbidity curve shows some parallel progression to the precipitation values. Yet, due to subsequent data gaps, this period is too short to make reliable statements. The same is true for the turbidities at the plant from October 2017 to February 2018, which are interrupted by frequent data gaps. Regarding coagulant dose rates, Sono fulfils the expectations from the precipitation curve better. Within 19 consecutive monthly values from July 2018 to January 2020, the progression of precipitation can be partly recognised, particularly regarding the peaks in October 2018 and May 2019. However, also here, many observations do not fulfil the expectations, e.g., regarding the influence of the all-time precipitation high in October 2019. Overall, the figures show that the degree of proportional correlation between precipitation and raw water turbidity, as well as between precipitation and coagulant dose rate, is most likely lower for Lirima and Sono compared to Malaba-Tororo.

Figure 43 provides time series of monthly mean raw water turbidity and coagulant dose rates for the case study DWTPs. As described before, a proportional correlation of both parameters to precipitation is assumed for Malaba-Tororo. Consequently, a correlation would also be expected between the two parameters. This is confirmed by the time series diagram in the figure. At Malaba-Tororo, monthly raw water turbidity and coagulant dose rates show similar progressions during the observation period. Peaks of both parameters mostly occur in the same months, e.g., in March 2017, September 2017, October 2018, and May 2019. Between those peaks, the time series of both parameters appear to progress almost in parallel, wherever data is available. In this context, it is important to note that raw water turbidity is applied with a logarithmic scale in the diagram, while coagulant dose rate is not. Hence, while illustrating a generally comparable progression, the amplitudes of turbidity are higher than the ones of coagulant dose rate.

As in the figures discussed above, the observations are not as clear for Lirima and Sono. This is mainly due to limited data availability for the time series of the two DWTPs, i.e., opportunities for a comparison of raw water turbidity and coagulant dose rate are fewer than for Malaba-Tororo. Nevertheless, generally comparable progressions can be observed for both parameters at Lirima from December 2017 to March 2018, and Sono from December 2018 to July 2019. Hence, it can be assumed that a certain degree of proportional correlation between raw water turbidity and coagulant dose rate exists within the data series for Lirima and Sono as well, albeit smaller than for Malaba-Tororo.

To investigate the interconnections just discussed more schematically, simple regression analyses were performed for the different combinations of parameters listed above. Table 5 shows the results in the form of coefficients of determination (R^2) for each of the relationships. They were calculated and presented based on the daily, weekly, and monthly data series, both before and after outlier analysis. Besides providing results for the linear functional relationships between the parameters, also values for the natural logarithmic form are indicated, where applicable. An asterisk indicates a negative slope of the corresponding regression equation.

The table shows that R^2 varies from 0.00, which is the lowest possible value and implies that no functional relationship exists at all, to values as high as 0.71, which indicates a comparatively high degree of correlation. In theory, the maximum value of R^2 is 1, which is though not likely to be achieved in practice (Kutner et al. 2005, p. 74). For most of the indicated relationships, Malaba-Tororo shows higher R^2 values compared to Lirima and Sono. This confirms the observations made for the time series diagrams before. Yet, the R^2 values seem to depend strongly on the temporal resolution of the considered data series, and on whether outliers were excluded for the calculation or not.

		Daily values		Weekly values		Monthly values	
Relationship	DWTP	R^2	n	R^2	n	R^2	n
Precipitation → Raw water turbidity	Lirima	0.0001 *(0.0017)*	303 *(294)*	0.0023* *(0.0033*)*	57 *(52)*	0.0017 *(0.1640*)* Ln: 0.0131 *(0.2877*)*	18 *(15)*
	Sono	0.0061* *(0.0125*)*	239 *(234)*	0.0529* *(0.0917*)*	48 *(46)*	0.0138* *(no outliers)* Ln: 0.0059 *(no outliers)*	17 *(17)*
	Malaba -Tororo	0.0165 *(0.0684)*	666 *(605)*	0.1292 *(0.2425)*	97 *(89)*	0.2226 *(0.6338)* Ln: 0.2054 *(0.4725)*	31 *(29)*
Precipitation → Coagulant use	Lirima	0.0021 *(0.0282)*	360 *(268)*	0.0071 *(0.0226)*	53 *(45)*	0.1098 *(no outliers)* Ln: 0.0407 *(no outliers)*	27 *(27)*
	Sono	0.0504 *(no outliers)*	443 *(443)*	0.2258 *(no outliers)*	69 *(69)*	0.3916 *(no outliers)* Ln: 0.3992 *(no outliers)*	24 *(24)*
	Malaba -Tororo	0.0756 *(0.0709)*	1,091 *(1,075)*	0.2641 *(0.2968)*	156 *(153)*	0.4380 *(0.5047)* Ln: 0.4069 *(0.4608)*	36 (35)
Precipitation → Coagulant dose rate	Lirima	0.0026 *(0.0068)*	359 *(353)*	0.0527 *(no outliers)*	53 *(53)*	0.0782 *(0.0686)* Ln: 0.1354 *(0.1317)*	25 *(23)*
	Sono	0.0009 *(0.0383)*	423 *(358)*	0.0242 *(0.1171)*	67 *(60)*	0.1716 *(0.3601)* Ln: 0.2212 *(0.4520)*	18 *(15)*

		Daily values		Weekly values		Monthly values	
	Malaba -Tororo	0.0740 *(0.0839)*	1,091 *(1,072)*	0.2681 *(0.2530)*	156 *(153)*	0.4018 *(no outliers)* Ln: 0.3829 *(no outliers)*	36 *(36)*
Raw water turbidity → Coagulant use	Lirima	0.1503 *(0.0591)* Ln: 0.0940 *(0.0507)*	87 *(77)*	0.2800 *(0.3781)* Ln: 0.4420 *(0.3781)*	14 *(6)*	0.0028 *(0.0453*)* Ln: 0.0008* *(0.1291*)*	13 *(10)*
	Sono	0.0483 *(0.0153)* Ln: 0.0048 *(0.0002*)*	248 *(243)*	0.0103 *(0.0000*)* Ln: 0.0010* *(0.0143*)*	48 *(46)*	0.0048 *(no outliers)* Ln: 0.0035 *(no outliers)*	18 *(18)*
	Malaba -Tororo	0.2287 *(0.4604)* Ln: 0.5617 *(0.5293)*	664 *(602)*	0.4420 *(0.6329)* Ln: 0.7145 *(0.6611)*	97 *(89)*	0.5698 *(0.4667)* Ln: 0.5589 *(0.5021)*	31 *(29)*
Raw water turbidity → Coagulant dose rate	Lirima	0.0944 *(0.0587)* Ln: 0.0671 *(0.0513)*	87 *(86)*	0.4244 *(0.1170)* Ln: 0.5546 *(0.1375)*	14 *(11)*	0.1312 *(0.3745*)* Ln: 0.1089 *(0.2923*)*	11 *(8)*
	Sono	0.0019* *(0.0097*)* Ln: 0.0006* *(0.0137*)*	242 *(220)*	0.0014* *(0.0010*)* Ln: 0.0037* *(0.0033*)*	46 *(44)*	0.0028* *(0.2277*)* Ln: 0.0502* *(0.2281*)*	16 *(14)*
	Malaba -Tororo	0.2126 *(0.4713)* Ln: 0.5137 *(0.5193)*	664 *(601)*	0.4504 *(0.5823)* Ln: 0.6648 *(0.6106)*	97 *(89)*	0.5262 *(0.3740)* Ln: 0.5299 *(0.4502)*	31 *(29)*

Table 5: Coefficients of determination (R^2) and number of values (n) for selected relationships between precipitation, raw water quality, and operating parameters for Lirima, Sono, and Malaba-Tororo DWTPs. Daily, weekly, and monthly resolution. Values in normal font refer to linear functional relationships, *italic font* refers to the natural logarithm (Ln). An asterisk (*) indicates a negative slope of the corresponding regression equation.

For example, for the relationship “Precipitation → Raw water turbidity”, R^2 values for Malaba-Tororo vary from only 0.02 for the daily resolution before outlier analysis up to 0.63 for the monthly resolution after outlier analysis. This shows that differences between the R^2 values can be immense, even though both describe the same relationship. In any case, it can be observed that the R^2 values for Malaba-Tororo are well above the values for Lirima and Sono for this relationship. The same applies for the relationship “Precipitation → Coagulant use”, for which Sono shows comparatively high R^2 values as well. The maximum R^2 value for this relationship can be observed for Malaba-Tororo for the monthly resolution after outlier analysis, namely of 0.50. Here, the R^2 for the linear functional relationship for Sono is at 0.39, while the natural logarithmic form shows a R^2 value of 0.40. The correlations for Lirima are considerably smaller for this relationship, regardless of the temporal resolution. The maximum R^2 of all evaluations is calculated for the relationship “Raw water turbidity → Coagulant use” at Malaba-Tororo, in logarithmic form and weekly resolution. As mentioned above, this maximum value is at 0.71. In comparison, the highest R^2 values for this relationship are at 0.44 for Lirima and only 0.01 for Sono. These numbers show that the R^2 values for this relationship clearly vary between the DWTPs, indicating the highest degree of proportional correlation at Malaba-Tororo, followed by Lirima and Sono. A similar observation can be made for the relationship “Raw water turbidity → Coagulant dose rate”, where the maximum R^2 values for Malaba-Tororo, Lirima and Sono are at 0.66, 0.55, and 0.23*, respectively. In contrast, the relationship “Precipitation → Coagulant dose rate” indicates the highest R^2 value of 0.45 for Sono, in logarithmic form and based on monthly values after outlier analysis. The maximum R^2 values of Malaba-Tororo and Lirima are at 0.40 and 0.14 for this relationship, respectively.

Many rows in Table 5 show that finer temporal resolutions result in lower R^2 values, i.e., that daily data series show less correlation compared to weekly and monthly data series for the same relationships. In fact, this observation is valid for all R^2 of the relationships "Precipitation → Coagulant use” and “Precipitation → Coagulant dose rate”, as well as for several individual R^2 from other relationships. As an example, the relationship “Precipitation → Coagulant dose rate” for Sono shows a R^2 of 0.04 based on daily values after outlier analysis, which indicates no notable correlation between the data series. Based on weekly data, R^2 is at 0.12, while for the monthly resolution, a value of 0.36 is determined. The latter indicates a moderate proportional correlation, as discussed above for Figure 42. A potential explanation for such observations is that individual daily values which are considerably higher or lower than the overall mean of a data series might disturb potentially existing correlations and decrease the R^2 value in the daily resolution. As daily values are aggregated to weekly or monthly sum and mean values, these individual values are smoothened out and have a smaller impact on R^2. Thereby, the aggregation to longer time periods can show underlying proportional correlations which were not visible in the daily data. However, there are also exceptions from this observation. The relationship “Raw water turbidity → Coagulant use” at Lirima indicates R^2 values for the daily, weekly, and monthly resolution of 0.15, 0.28, and 0.00, respectively. Here, the highest correlation can be observed based on the weekly data series. A similar observation can be made for the relationship “Raw water turbidity → Coagulant dose rate” at Lirima. Hence, it appears that in some cases, a monthly resolution might miss certain information and details which would be relevant to recognise existing correlations.

Regarding the outlier analysis, mixed observations can be made. In some cases, the exclusion of outliers increases R^2 considerably, e.g., for the relationship “Precipitation → Raw water turbidity” at Malaba-Tororo, or for “Precipitation → Coagulant dose rate” at Sono. In other cases, the exclusion of outliers does not change the R^2 values much, or even leads to a decrease in R^2. For the relationships “Raw water turbidity → Coagulant use” and “Raw water turbidity → Coagulant dose rate”, mixed results are obtained.

In several cases, negative regression coefficients of the corresponding regression equations were retrieved, as indicated with an asterisk in the table. While this seems unintuitive at first, it mainly occurs with low R^2 values of $R^2 < 0.1$, which speaks more for statistical coincidences than for de facto inversely proportional relationships. Yet, for the monthly resolution, also higher R^2 values are observed for Lirima and Sono. These include values of up to 0.29* for the logarithmic relationship “Precipitation → Raw water turbidity”, and up to 0.37* for the logarithmic relationship “Raw water turbidity → Coagulant dose rate”. Regarding the former, Price and Heberling (2018, p. 196) mention that precipitation may not only lead to deteriorated water quality via increased runoff, but also to a dilution effect that reduces contaminant concentrations at the water intake of a DWTP. The authors state that the overall effect of increased precipitation can be ambiguous, depending on the importance of the runoff relative to this described dilution effect. It is conceivable that higher R^2 values for the relationship “Precipitation → Raw water turbidity” in combination with a negative slope in the corresponding functional equation are related to this dilution effect. For the latter observation, a potential explanation might be in the dosing strategy applied at Lirima and Sono, which is prone to over- or underdosing of coagulant chemicals and might not react ideally to raw water turbidity (see Chapter 4.1).

To better visualise the simple regression analyses for which the R^2 values were just discussed, scatterplot diagrams for selected relationships in different temporal resolutions are presented in the following. Figure 44 shows a scatterplot diagram for the relationship “Precipitation → Raw water turbidity”, based on weekly values after outlier analysis. As expected from the results discussed in Chapter 4.2.2, the figure illustrates that raw water turbidity at Lirima and Sono is considerably lower compared to Malaba-Tororo. Despite varying precipitation sums, the mean turbidity values at both upstream DWTPs stay below 60 NTU, through which they are practically not distinguishable in the scale of the diagram. In contrast, Malaba-Tororo includes mean turbidity values of more than 1,000 NTU. In the weekly resolution, no correlation can be observed for Lirima ($R^2 = 0.00$), and only a weak correlation for Sono ($R^2 = 0.09$). The linear functional equations for both DWTPs include negative regression coefficients, which might be due to statistical coincidences given the low R^2 values, or due to a dilution effect, as described before. In any way, the regression coefficients of both functional equations are comparatively small with -0.01 for Lirima and -0.09 for Sono. Hence, even if the R^2 values were higher, these numbers would not plead for a strong influence of precipitation on raw water turbidity at both DWTPs. In contrast, Malaba-Tororo shows a moderate linear correlation ($R^2 = 0.24$) and a higher slope of the functional equation of +5.4608. This implies that if the functional equation was correct in reality[7], +1 mm/week of precipitation would result in an average weekly raw water turbidity of +5.4608 NTU. Due to the distribution of the data points of Malaba-Tororo, it can be observed that particularly elevated weekly mean values of raw water turbidity, e.g., of 1,000 NTU and above, are not well captured by the linear functional equation. Here, the projected regression curve shows strong deviations to the de facto measured values, which is observed less for smaller turbidity values below the regression line.

[7] Due to the value of R^2 below 1, the projection expressed by the functional equation is subject to uncertainties and can merely be an estimation of the real conditions. Therefore, while the functional equation was calculated correctly, the word "correct" in this context refers to the application of the projected values to reality.

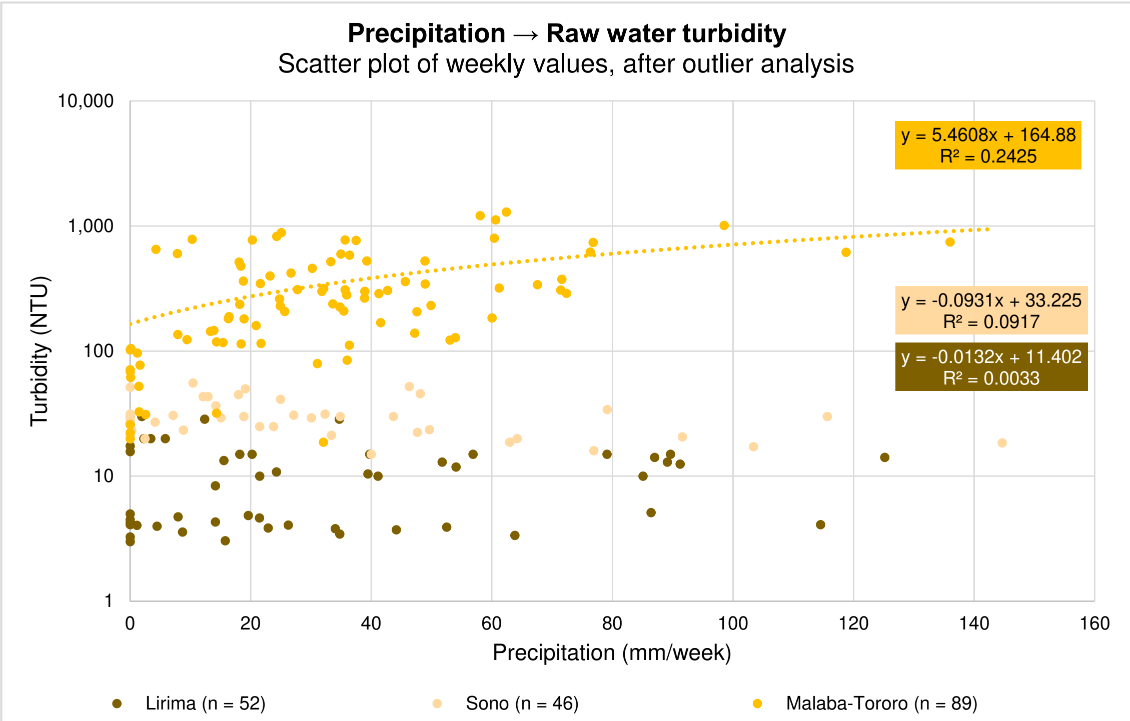


Figure 44: Scatterplot diagram for the relationship of precipitation sum to mean raw water turbidity at the intakes of Lirima, Sono, and Malaba-Tororo DWTPs. Weekly values from January 2017 to January 2020, after outlier analysis. The linear regression graphs are provided with their functional equations and coefficients of determination (R^2). Y-axis in logarithmic scale.

Figure 45 shows a scatterplot diagram for the relationship "Precipitation → Coagulant use", based on all available monthly values. As expected from the results discussed in Chapter 4.2.4, the figure illustrates that coagulant use increases from Lirima via Sono to Malaba-Tororo. Despite varying precipitation sums, the mean coagulant use stays below 40 kg alum/d at Lirima, and below 115 kg alum/d at Sono. In contrast, Malaba-Tororo includes mean coagulant uses of more than 300 kg ACH/d, which would equal alum uses of more than 900 kg/d. Also, the peak value 568.98 kg ACH/d (1,724.05 kg alum equivalent/d) from May 2019 is clearly visible in the diagram. Even though the correlation is analysed based on the monthly data series, only a weak linear correlation can be observed for Lirima (R^2 = 0.11), while a moderate linear correlation was calculated for Sono (R^2 = 0.39). As expected, the highest proportional correlation is observed for Malaba-Tororo (R^2 = 0.44). If a functional form based on the natural logarithm is applied, the correlation gets weaker for Lirima (R^2 = 0.04), while it stays almost the same for Sono (R^2 = 0.40) and Malaba-Tororo (R^2 = 0.41). Unlike for the relationship discussed previously, the identified functional equations show positive regression coefficients for all three DWTPs, as expected. However, for Lirima, the slope is comparatively small with only +0.0262. This implies that if the functional equation was correct, +1 mm/month of precipitation would result in an average alum use of +0.0262 kg/d (26.2 g/d) at the DWTP. Against the background of several hundred kg of alum used at the DWTP per month, this would speak for a rather small influence of precipitation on alum use. In comparison, the slope calculated for the functional equation at Sono of +0.1719 is already about 6.6 times higher than the one of Lirima. Here, +1 mm/month of precipitation would result in an average alum use of +0.1719 kg/d (171.9 g/d) at the DWTP. For every additional mm of precipitation, this would lead to an increase in alum use of about 5 kg per month. As expected, the slope of the linear functional equation for Malaba-Tororo is the highest among the three DWTPs. The value of +0.8941 is about 5 times the value of Sono, and about 34 times the value of Lirima. If the functional equation was correct, +1 mm/month of precipitation would result in an average ACH use of +0.8941 kg/d (2.71 kg alum equivalent/d) at the DWTP. For every additional mm of precipitation, this would mean an increase in ACH use of about 27 kg per month or 326 kg per year.

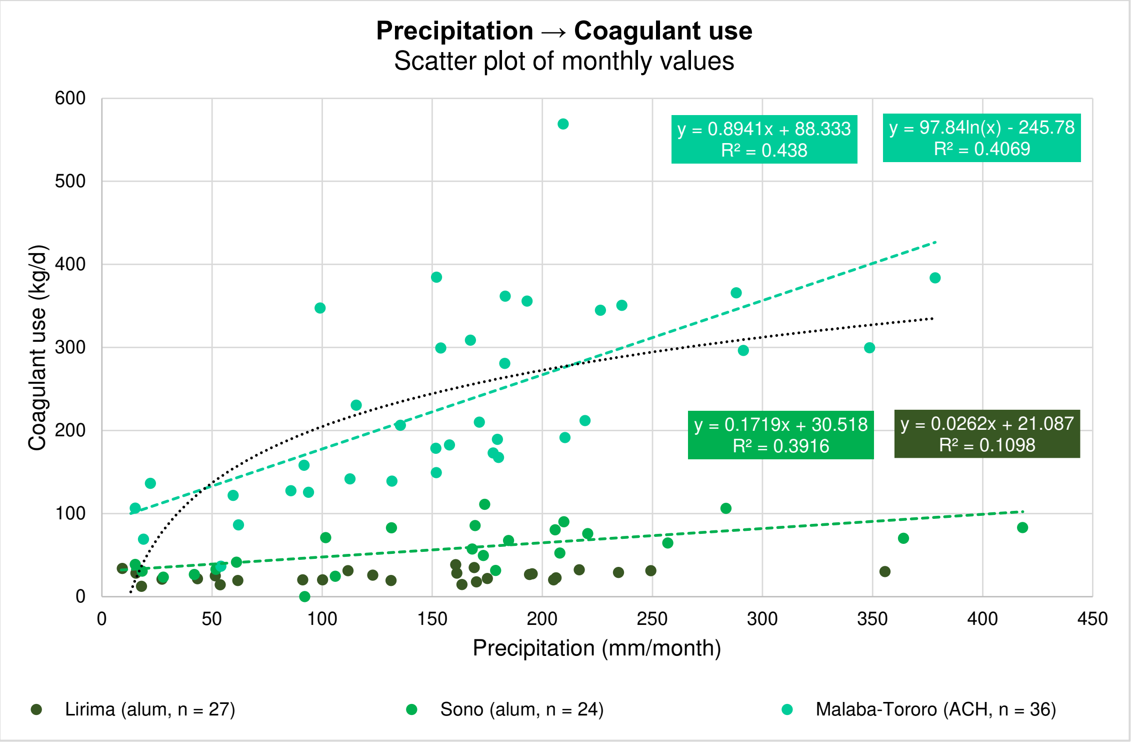


Figure 45: Scatterplot diagram for the relationship of precipitation sum to mean coagulant use at Lirima, Sono, and Malaba-Tororo DWTPs. Based on all available monthly values from January 2017 to January 2020. The linear regression graphs are provided with their functional equations and coefficients of determination (R^2).

For an increase in precipitation, the presented numbers imply a considerable increase in coagulant quantities required for water treatment at Malaba-Tororo, while moderate changes are observed for Sono and almost no changes for Lirima. However, it is important to note the presented numbers should not be perceived as correct predictions of reality. As the R^2 values related to all presented functional equations are clearly below 1, a high uncertainty exists for the predictions. The functional equations are therefore only approximations to reality. Based on the results, it appears very likely that the parameter precipitation alone is not sufficient and that further factors influence the parameter coagulant use at the case study DWTPs. If these other influencing factors are considered as well, the coagulant use quantities might be estimated more precisely.

Figure 46 shows a scatterplot diagram for the relationship “Raw water turbidity → Coagulant use” based on the weekly resolution data series. In contrast to Figure 44 for which turbidity outliers were excluded, Figure 46 includes all weekly values and hence shows also higher turbidity averages of up to 4,824.43 NTU at Malaba-Tororo. As discussed in Chapter 4.2.4 and previously in this chapter, the figure indicates that coagulant use quantities increase from Lirima via Sono to Malaba-Tororo. Therefore, the evaluation was split into two diagrams with different scales, one for the two upstream DWTPs, and one for Malaba-Tororo located downstream within the SMMRB. The diagram shows that for Lirima, only a comparatively small number of 14 weekly observations is included. This is because weekly values for both raw water turbidity and coagulant use are required for the same points in time to be considered in the evaluation. Since the two weekly data series at Lirima overlap only from 27th November 2017 to 4th March 2018, only 14 values can be considered for this relationship. For the available values, a moderate correlation with R^2 values of 0.28 for the linear and 0.44 for the logarithmic functional form can be identified. This shows that the correlation between the parameters is higher if a logarithmic functional relationship is assumed. The slope of the linear functional equation is at +0.2198, which implies that if this functional equation was correct, an average turbidity of +1 NTU/week would result in an average alum use of +0.2198 kg/d (219.8 g/d) or about 1.54 kg/week at the DWTP. For the logarithmic functional equation, such predictions cannot be made since the increase in average alum use resulting from +1 NTU/week depends on the respective baseline turbidity level the prediction starts from. For Sono, a point cloud without any distinguishable trend is observed in the diagram. This is confirmed by the corresponding R^2 values of 0.01 (linear form) and 0.00* (logarithmic form). These values underline that practically no correlation exists between the parameters at Sono. As expected, the highest proportional correlation for the relationship is observed for Malaba-Tororo, with R^2 values of 0.44 for the linear and 0.71 for the logarithmic functional form. In fact, the latter value is the highest R^2 value retrieved for any of the simple regression analysis performed in this thesis. As for Lirima, the results indicate that the correlation between the parameters is higher if a logarithmic functional relationship is assumed compared to a linear one. This can be confirmed visually from the scatterplot, which shows that both the values with maximum raw water turbidity of 4,824.43 NTU, and with maximum ACH use of 461.57 kg/d are closer to the logarithmic progression, i.e., are captured better by the logarithmic functional equation compared to the linear one.

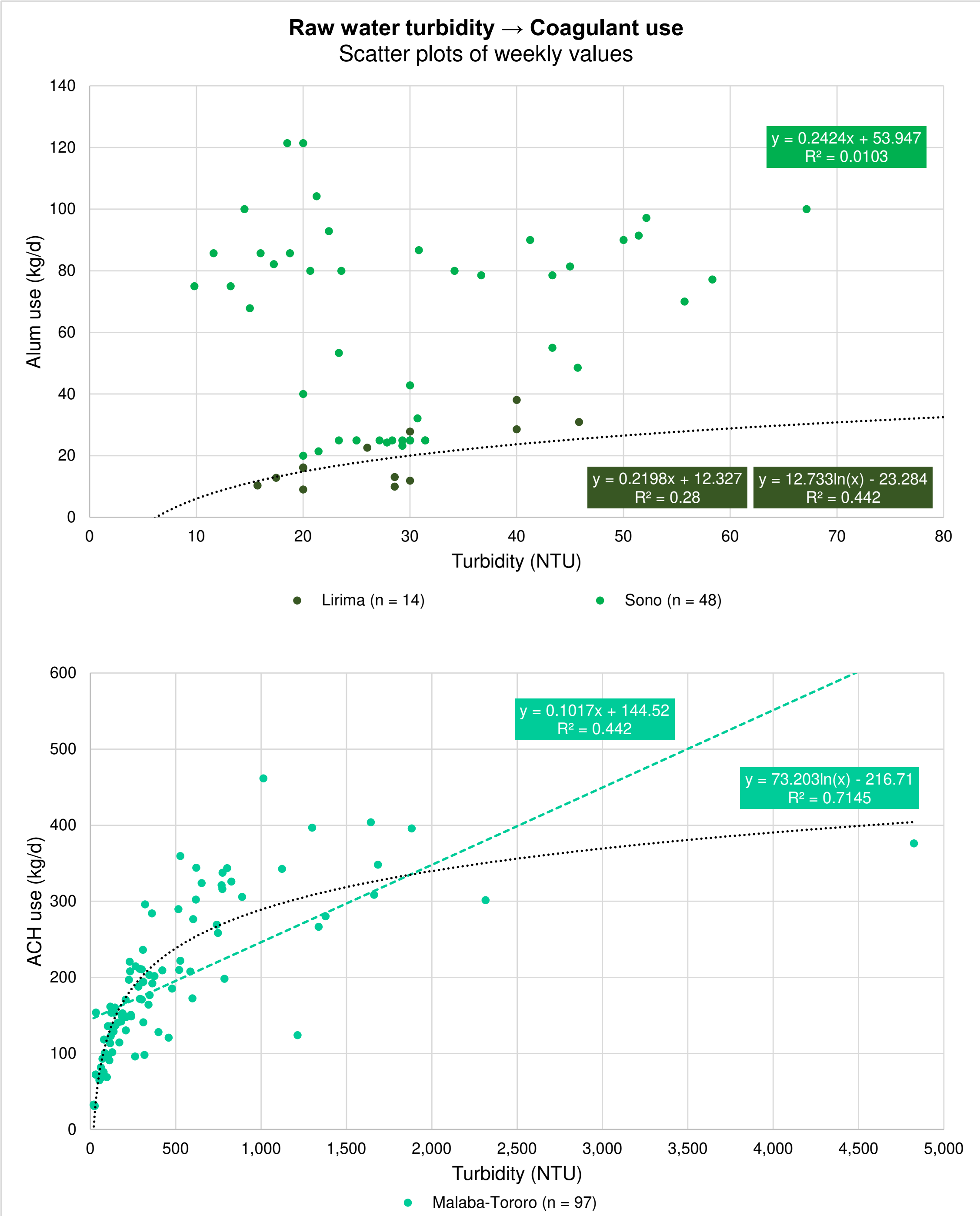


Figure 46: Scatterplot diagrams for the relationship of mean raw water turbidity to mean coagulant use at Lirima, Sono, and Malaba-Tororo DWTPs. Based on all available weekly values from September 2016 to January 2020. The linear regression graphs are provided with their functional equations and coefficients of determination (R^2).

Yet, if the two values mentioned were removed from the evaluation, R^2 would be at 0.57 for the linear and 0.71 for the logarithmic functional form. Hence, even if excluding the two values that visually plead for a logarithmic relationship, the logarithmic form would still describe the relationship between the data series better. For the linear form at Malaba-Tororo, the slope of the functional equation is at +0.1017. This implies that if the functional equation was correct, an average turbidity of +1 NTU/week would result in an average ACH use of +0.1017 kg/d (101.7 g/d) or about 0.71 kg/week at the DWTP. Per year, every increase in mean turbidity of +1 NTU would increase coagulant uses by 37.12 kg ACH (112.49 kg alum equivalent) at Malaba-Tororo, compared to 80.23 kg alum at Lirima. As described before, such predictions cannot be made for the logarithmic form.

The last simple regression analysis for which the scatterplot diagrams will be discussed is the relationship" "Raw water turbidity → Coagulant dose rate". This time, the daily data series of both parameters after outlier analysis were evaluated in Figure 47. As before, the evaluation was split into two diagrams with different scales, one for the two upstream DWTPs, and one for Malaba-Tororo located downstream within the SMMRB. As discussed above for Figure 46, the number of available daily values for Lirima is smaller compared to Sono and Malaba-Tororo, since the two required data series overlap only for a short period. In the upper diagram for Lirima and Sono, it is noteworthy that specific numbers of the independent variable raw water turbidity are provided with several dependent data points each. This affects mainly turbidities of 10, 20, 25, 30, 40, 50, and 60 NTU, for which the data points form straight vertical lines distinguishable in the diagram. These repeating turbidity values at Lirima and Sono were observed in Figure 21 before. In Figure 46, it appears that only a few of the indicated data points do not include one of the raw water turbidities stated above, to be precise only two of 86 data points for Lirima, and 53 of 220 data points for Sono. As discussed in Chapter 4.2.2, no reason for these repeating turbidity values could be determined from the data. It must be assumed that the true turbidities in the raw water were, at least slightly, different than the ones in the record books, i.e., that more variable turbidities were present in the raw water on the respective sampling days. This also influences the trustworthiness of the evaluations presented for Lirima and Sono in the scatterplot diagram. Besides the discussed turbidity patterns, the graphic representation of the data points indicates no trends for both DWTPs but shows rather point clouds with seemingly randomly arranged values. The R^2 for both DWTPS are low, indicating no noticeable correlation. Furthermore, the trend lines include only small regression coefficients in their functional equations, which does not plead for a relevant impact of raw water turbidity on coagulant dose rate during the observed period. A reason for this observation could be the frequent repetition of certain raw water turbidity values mentioned above, through which a potential correlation that would be visible in case of more precise original values might be removed.

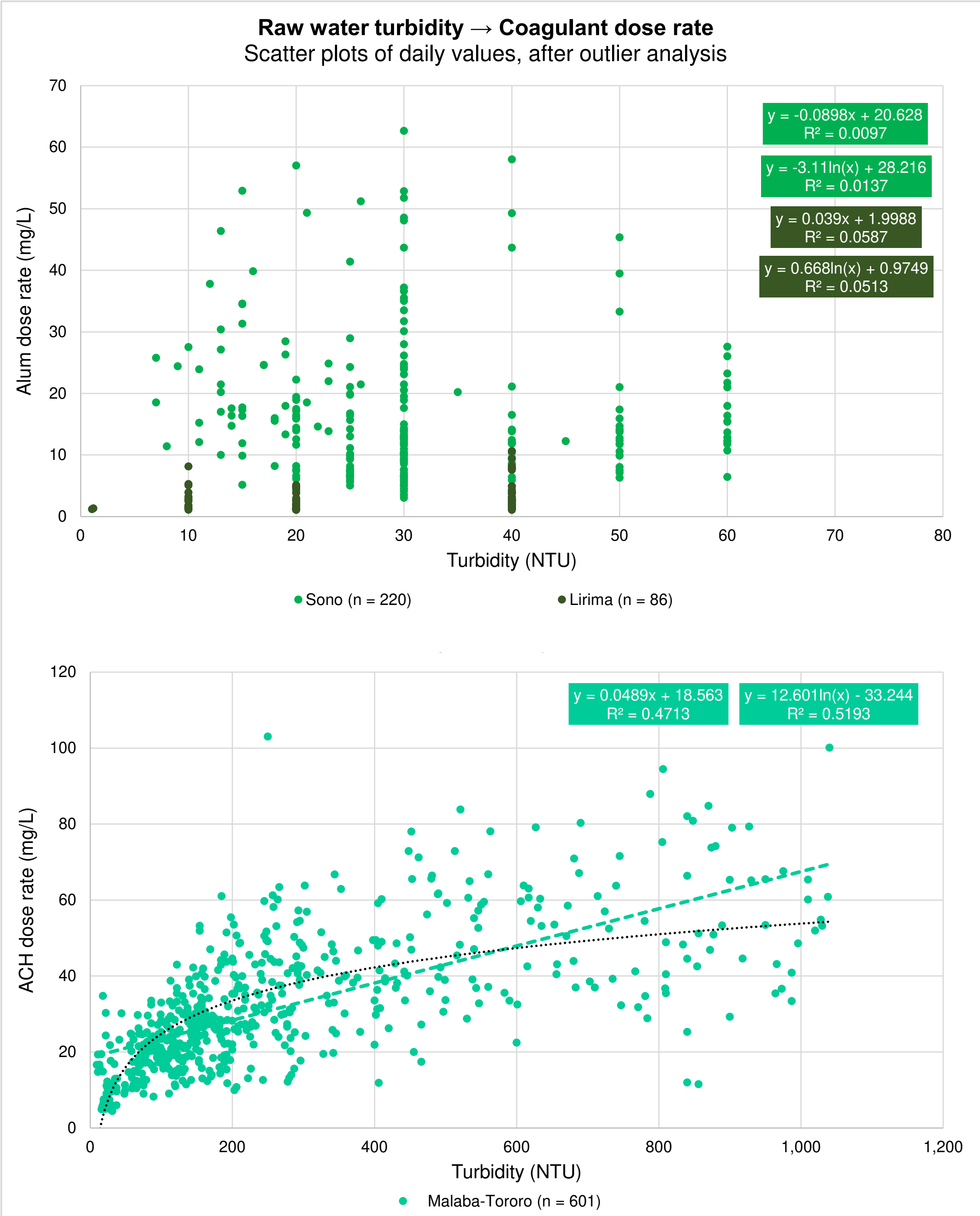


Figure 47: Scatterplot diagrams for the relationship of mean raw water turbidity to mean coagulant dose rate at Lirima, Sono, and Malaba-Tororo DWTPs. Daily values from September 2016 to January 2020, after outlier analysis. The linear regression graphs are provided with their functional equations and coefficients of determination (R^2).

For Malaba-Tororo, the scatterplot diagram in Figure 47 shows no repeating turbidity values, but a dynamic progression as expected from the results discussed above for Figure 46. Even though a daily resolution was selected for the evaluation which usually tends to deliver lower correlations compared to weekly or monthly ones, the R^2 values are at 0.47 for the linear and 0.52 for the logarithmic form. These values indicate a comparatively high degree of proportional correlation between raw water turbidity and coagulant dose rate at Malaba-Tororo based on daily values. The slope of the linear functional equation is at +0.0489, which implies that if this functional equation was correct, an average daily turbidity of +1 NTU would result in an average daily ACH dose rate of +0.0489 mg/L (48.9 g/L) at the DWTP. As an example for calculation, an average decrease of 10 NTU due to improved stream water quality would result in -0.489 mg ACH/L (-1.48 mg alum equivalent/L) required for water treatment. In the diagram, it appears that one data point with a turbidity of 250 NTU and ACH dose rate of 103 mg/L disturbs the general distribution of the data. If this value would be excluded, this results in R^2 values of 0.49 for the linear and 0. 53 for the logarithmic functional form. This shows that the removal of one value out of 601 can already notably change the results, which illustrates the sensitivity of the results and the relevance of the performed outlier analysis.

4.4. Multiple regression model

Based on the deliberations described in Chapter 3.4.4, the empirical relationship of raw water quality, environmental factors, and treatment effort at the case study DWTPs during the observation period can be described according to Equation (10).

$$\ln(\boldsymbol{Coag_t}) = \beta_0 + \beta_S \times \ln(Season_t) + \beta_R \times \ln(Rain_t) + \beta_{Rwp} \times \ln(Rwp_t) + \boldsymbol{\beta_{WQ}} \times \ln(Turb_t) + \varepsilon_t \qquad (10)$$

In the equation, $Coag_t$ represents coagulant chemical use (in kg/week), $Season_t$ represents seasonality (in mm), $Rain_t$ represents precipitation (in mm/week), Rwp_t represents raw water pumped (in m^3/week), and $Turb_t$ represents raw water turbidity (in NTU). β_i are the respective regression coefficients. In line with Warziniack et al. (2017, p. 6), the error term (ε_t) is assumed to be normally distributed, with mean zero and constant variance. The expanded multiple regression equation to include all case study DWTPs was established according to Equation (11).

$$\ln(\boldsymbol{Coag_t}) = \beta_0 + \beta_S \times \ln(Season_t) + \beta_R \times \ln(Rain_t) + \beta_{Rwp} \times \ln(Rwp_t) + \boldsymbol{\beta_{WQ}} \times \ln(Turb_t) + \beta_{DWTP2} \times dv_{Sono} + \beta_{DWTP3} \times dv_{Malaba-Tororo} + \varepsilon_t \qquad (11)$$

dv_{Sono} and $dv_{Malaba\text{-}Tororo}$ are dummy variables to differentiate between the respective case study DWTPs.

Comparison with the literature

After the parameters disinfectant chemical use, energy consumption, and backwash water volume were excluded as dependent variables, the multiple regression modelling approach remained with one key response variable, namely coagulant chemical use. A model with a single response variable is referred to as a univariate model (Price and Heberling 2018, p. 199). While several of the studies presented in Chapter 2.4.3 included more than one response variable (i.e., are multivariate models), Forster and Murray (2007, p. 117) argued that the approach applied in this thesis is reasonable. Following the authors, changes in raw water quality mainly affect chemical treatment costs, while any other expenses (i.e., nonchemical treatment costs for labour, energy, etc.) are exclusively influenced by the type of treatment technology and the volume of treated water. As the authors were interested in both treatment cost types, they developed two multiple regression equations to cover both. However, for the research objectives of the present thesis (see Chapter 1.2), it is sufficient to focus on one equation using coagulant chemical use as a response variable. Thereby, the present thesis principally follows the approach by Moore and McCarl (1987), except that no pH adjusting chemicals were applied at the Ugandan case study DWTPs. Also Westling et al. (2020) focused on chemical use as the dependent variable to represent drinking water production costs, while omitting other variable cost factors. The authors wrote that they were informed by treatment plant operators that chemical use, more than any other factor, varies with varying raw water quality in the short run.

Expected modelling results

Regarding the control variable seasonality, wet season values are expected to increase coagulant use at the case study DWTPs due to elevated soil moisture contents in the river basin. Thereby, the mobilisation of sediments and particles and their delivery to streams is facilitated. Furthermore, an overall increased frequency, duration, and intensity of rainfall during the wet season is expected to result in higher dosing decisions, particularly at the DWTPs of Lirima and Sono where dosing is determined by professional experience of the plant overseers considering the weather conditions. Overall, the regression coefficient β_S is expected to be positive. Higher values of the control variable precipitation are expected to increase coagulant use as it is a key factor for the mobilisation of sediments and particles in a river basin. Furthermore, precipitation directly leads to decisions for higher doses of coagulant at some of the case study DWTPs. For the dilution argument by Holmes (1988, p. 362), Price and Heberling (2018, p. 198) and Vincent et al. (2016, p. 64), no major impact on the results is expected due to the predominant agricultural land use in the SMMRB and the resulting high potential for rainfall-induced erosion. Overall, the regression coefficient β_R is expected to be positive. Higher values of the control variable raw water pumped are expected to increase the treatment chemical use, and vice versa. Thereby, the coagulant dose rate which is critical for the removal of sediments and particles is kept steady in case of constant raw water qualities.

Hence, the regression coefficient β_{Rwp} is expected to be positive. Higher values for the explanatory variable raw water turbidity are expected to increase coagulant use at the case study DWTPs, as consistently indicated in the literature (see Chapters 2.2.3 and 2.4) and underlined by the results from the simple linear regression analysis (see Chapter 4.3). The presence of elevated turbidity levels in the inflowing water requires to increase coagulant doses at the DWTPs to reduce sediment and particle contents and achieve the desired final water quality. Therefore, the regression coefficient β_{WQ} is expected to be positive.

The dummy variables for Sono and Malaba-Tororo are difficult to predict. If all other independent parameters would be equal (i.e., seasonality, precipitation, processed water volumes, raw water turbidity), the dummy variables would mainly capture differences in treatment efficiency and deviations in human coagulant dosing decisions at the plants, e.g., potential over- or underdosing due to misjudgement of the rainfall or raw water conditions. On the one hand, Lirima is the most recently constructed of the case study DWTPs, which speaks for higher treatment efficiency at the plant compared to Sono and Malaba-Tororo. On the other hand, the jar-test based determination of coagulant doses at Malaba-Tororo promises more precise results and hence higher accuracy than the experience-based estimations of the plant overseers at Lirima and Sono. For Lirima and Malaba-Tororo, these effects could balance each other out, which would imply a regression coefficient β_{DWTP3} of close to 0 (Lirima was used as a reference and hence has no separate dv). Yet, also other influencing factors are conceivable which may affect the results. In any case, the value of the regression coefficient β_{DWTP2} for Sono is expected to be positive, as the DWTP is neither newly constructed, nor coagulant dosing is based on jar tests. In addition, Sono was affected strongest by irregular production and interruptions (see Figure 28 and Figure 29), which may further decrease treatment efficiency and result in a higher value for β_{DWTP2}.

4.5. Multiple regression results and water-quality elasticities

The estimation results from the multiple regression analysis are shown in Table 6.

	Dependent variable ***Coag***	
Independent variables	Malaba-Tororo *Equation (10)*	Lirima, Sono, and Malaba-Tororo *Equation (11)*
Season	0.047*** (0.013)	0.010 (0.009)
Rain	0.018** (0.009)	0.013* (0.007)
Rwp	-0.252 (0.247)	0.682*** (0.107)
Turb	0.358*** (0.031)	0.389*** (0.035)
Constant	7.513*** (2.633)	-3.791*** (1.164)
dv Sono	-	1.532*** (0.136)
dv Malaba-Tororo	-	2.487*** (0.127)
Observations	97	142
R^2	0.808	0.937
Adjusted R^2	0.799	0.935
Residual Std. Error	0.261 (df = 92)	0.350 (df = 135)
F Statistic	96.557*** (fc = 4; 92)	336.916*** (fc = 6; 135)
Note:	***p<0.01; **p<0.05; *p<0.1	

Table 6: Multiple regression analysis results from the univariate model presented in Chapter 4.4. The middle column shows the results for the DWTP of Malaba-Tororo based on Equation (10). The right column shows the results including all case study DWTPs based on Equation (11). All available weekly values were used as input data, including outliers. Indicated are the regression coefficients β_i, and corresponding standard errors (SE) in brackets. Asterisks indicate the respective p-values.

Estimation for Malaba-Tororo

Based on 97 weekly observations from January 2017 to November 2018, the estimation for Malaba-Tororo shows an adjusted R^2 of 0.80. This implies that 80 % of the dependent variable could be explained by the independent variables in the model. Most regression coefficients are significant at the 1 % level. Only rainfall was determined as significant at the 5 % level, while raw water pumped was identified as not significant.

As expected, the regression coefficients for seasonality and rainfall are positive. This indicates that the presence of the wet season as well as increasing precipitation lead to elevated weekly coagulant uses at Malaba-Tororo. The rainfall elasticity was calculated to 0.018, implying that 1 % decrease in precipitation sum per week leads to a 0.018 % decrease in weekly ACH use at the DWTP, and vice versa. Other than expected the regression coefficient for raw water pumped has a negative sign. Such observations were explained by the literature with a decrease in treatment chemical use due to economies of scale and factor prices (e.g., use of more specialised management systems, purchasing of bigger quantities of inputs potentially lowers per unit costs) (Forster et al. 1987, p. 350; Forster and Murray 2007, p. 119; Holmes 1988, p. 359). However, the variable was determined as not significant. This implies that the volume of processed water does not influence coagulant dosing decisions at the DWTP as much as other influencing factors. This observation might be due to comparatively stable operations at the DWTP, including rather constant raw water pumped values (see Figure 28). If the raw water pumped volumes are more or less constant, it is expected that other factors mainly influence coagulant dosing at the DWTP.

For raw water turbidity, the regression coefficient is positive, as expected. The water-quality elasticity was determined to 0.358, implying that a 1 % decrease in stream water turbidity leads to a 0.358 % reduction in coagulant chemicals at sample averages. Excluding the insignificant raw water pumped variable leads to only minor changes in the estimated results for the other variables. For example, the rainfall elasticity would remain at 0.018, while the turbidity elasticity would increase only slightly to 0.361.

Estimation for Lirima, Sono, and Malaba-Tororo

The second estimation considering all case study DWTPs is based on 142 weekly observations from January 2017 to April 2019. The input data includes 13 weekly observations from Lirima, 32 from Sono, and 197 from Malaba-Tororo. The estimation shows an adjusted R^2 of 0.94. This implies that 94 % of the dependent variable could be explained by the independent variables in the model. Most regression coefficients are significant at the 1 % level. In contrast to the previous estimation, this is also true for raw water pumped. Unlike before, rainfall was determined as significant at the 10 % level, while the seasonality was identified as not significant.

As expected, the regression coefficients for seasonality and rainfall are positive. This indicates that the presence of the wet season as well as increasing precipitation lead to elevated weekly coagulant uses at the case study DWTPs. The rainfall elasticity was calculated to 0.013, implying that 1 % decrease in precipitation sum per week leads to a 0.018 % decrease in weekly coagulant use in average over the three DWTPs. This elasticity is close to the value of 0.018 calculated for Malaba-Tororo alone. However, the seasonality was determined as not significant, and rainfall as less significant compared to the estimation for Malaba-Tororo. This implies that when considering all three case study DWTPs, overall coagulant dosing decisions are made independently from the season and are less influenced by precipitation. Since the situation for Malaba-Tororo was analysed separately before, this change can be clearly attributed to the influence of Lirima and Sono. Yet, the observations contradict the expectations for the two upstream DWTPs. According to the respective plant overseers (see Chapter 4.1), coagulant dosing decisions are made based on their professional experience under consideration of the weather conditions, and later verified with jar test experiments. The overseers stated that rainfall in the areas of Lirima and Sono leads to a direct increase of the alum dosage at the DWTPs, without any time delay. However, the results show that other influencing factors have greater impact on coagulant dosing decisions at Lirima and Sono than seasonality and rainfall. This might be due to the comparatively small relevant upstream catchment areas of the two DWTPs (43 km² for Lirima, 94 km² for Sono) compared to the one of Malaba-Tororo (1,203 km²). This means that the area for potential sources and mobilising factors of sediments and particles is smaller at Lirima and Sono compared to Malaba-Tororo. The influence of season and precipitation might hence be perceived as less significant by the plant overseers, thereby contributing less to their dosing decisions than other influencing factors.

In contrast to the previous estimation, the regression coefficient of raw water pumped was significant at the 1 % level. From the argumentation made above for raw water pumped at Malaba-Tororo, this was expected. As Figure 28 shows, while Malaba-Tororo shows comparatively stable operations and rather constant raw water pumped values during the observation period, this cannot be observed for Lirima and Sono. For both upstream DWTPs, the raw water volumes clearly vary over time. Therefore, it is comprehensible that raw water volumes have a significant impact on coagulant use in case all three case study DWTPs are considered. As expected, the regression coefficient for raw water pumped has a positive sign, indicating that higher processed water volumes increase the use of coagulant chemicals at the plants. The processed water volume elasticity was calculated to 0.682, implying that 1 % decrease in raw water pumped per week leads to a 0.682 % decrease in weekly coagulant use in average over the three DWTPs, and vice versa.

For raw water turbidity, the regression coefficient is positive, as expected. The water-quality elasticity was determined to 0.389, implying that a 1 % decrease in stream water turbidity leads to a 0.389 % reduction in treatment effort in average over the three DWTPs. The elasticity is close to the value of 0.358 calculated for Malaba-Tororo alone, indicating a difference of only 0.031 between the two estimations. Thereby, it can be concluded that the response of the three case study DWTPs to varying raw water turbidities, expressed by coagulant chemical use, is comparable. The result is achieved despite several differences between the plants in terms of raw water qualities, plant sizes, applied coagulant type, and operational management.

The dummy variables for Sono and Malaba-Tororo are both positive, indicating that if all other variables would be set equal, the two DWTPs consume more coagulant chemicals per week than Lirima. Other than expected the regression coefficient for the Malaba-Tororo dv is highest with 2.487, while the coefficient for the Sono dv is at 1.532. Consequently, the results indicate that treatment efficiency and accuracy of coagulant dosing decisions is lowest at Malaba-Tororo, better at Sono, and best at Lirima. While this result was expected for Lirima as it is the most recently constructed of the three case study DWTPs, the results for the other two DWTPs are surprising. It appears that significantly more coagulant chemicals are dosed at Malaba-Tororo per raw water turbidity and produced water volume than in both upstream DWTPs. The observation could be explained by the fact that Malaba-Tororo generally faces the most impaired intake water qualities among the three DWTPs. This might result in overdosing decisions at the plant to achieve a safety margin in the water treatment process, i.e., to be on the safe in preventing elevated levels of particle-related parameters in the final water. Another explanation might be in the methodological design of the present study. The conversion factor of 0.33 applied to calculate alum equivalent use based on ACH use might be overestimated. The factor was retrieved from the literature and was not adjusted to the conditions in the SMMRB. Furthermore, it is worth mentioning that by the design of the multiple regression model, the dummy variables for Sono and Malaba-Tororo capture any differences that potentially exist between the DWTPs. Besides differences regarding treatment efficiency and accuracy of coagulant dosing decisions, this might include other disparities as well which were not known to the author. To retrieve the respective elasticities for the dummy variables, the related regression coefficients require a transformation as follows (e.g., Warziniack et al. 2017, pp. 13–14):

$$Elasticity\ \mu_{DWTP2} = (e^{1.532} - 1) \times 100 = 363\ \% \quad (12)$$

$$Elasticity\ \mu_{DWTP3} = (e^{2.487} - 1) \times 100 = 1{,}103\ \% \quad (13)$$

The results imply that if all other independent variables would be set equal (i.e., seasonality, precipitation, processed water volumes, and raw water turbidity), the DWTP of Sono would require about 3.6 times (363 %) as much coagulant chemical per week as Lirima, while Malaba-Tororo would require about 11 times (1,103 %) as much.

Comparison with the literature

The turbidity elasticities were determined to 0.358 considering only Malaba-Tororo, and 0.389 considering all case study DWTPs. The difference between the elasticities of the two analyses is rather small, which confirms the results. Following Equation (9), the results can be presented as follows (after Price, Heberling 11/8/2017, p. 12):

$$Turbidity\ elasticity\ \mu = \frac{\Delta\ Chemical\ treatment\ effort\ (\%)}{\Delta\ Source\ water\ turbidity\ (\%)} = \mathbf{0.358}\ to\ \mathbf{0.389} \quad (14)$$

As Price and Heberling (2018, 199, 202) pointed out, turbidity elasticities in the literature range from an unexpected -0.11 to 0.30, which is close to the results from the present thesis. The authors further calculate an average of 0.14 among all 12 studies indicating turbidity elasticities. Hence, the results from the present thesis are clearly higher than the average, and even higher than the maximum turbidity elasticity indicated in the literature. However, the results seem acceptable for different reasons:

- According to the respective plant overseers at the case study DWTPs, sediments and particles, represented by the parameter turbidity, are the main water quality related challenge for drinking water treatment in the SMMRB. This has an amplifying effect on coagulation requirements and dosing decisions at surface water treatment plants in the study area, which may lead to elevated coagulant chemical uses and hence higher turbidity elasticities.
- Findings from the literature, as well as the results from the present thesis, are highly context specific. In the present research, three individual case study DWTPs were considered, not an average over multiple plants as done in several publications. Therefore, elevated results from individual DWTPs in the SMMRB

(i.e., Malaba-Tororo) have notable effects in the present study and are not balanced out by smaller observations.

- At the case study DWTPs, coagulant dosing decisions are predominantly based on professional experience considering the weather conditions. Therefore, excess dosing of coagulants is possible, which implies higher turbidity elasticities.

<u>Correlation between observed and predicted values</u>

Figure 48 illustrates the correlation between the observed and predicted values of weekly coagulant use for the DWTP of Malaba-Tororo. The upper diagram shows the linearised values in natural logarithmic form, as depicted in Table 6. When recalculating the values to ACH quantities that were de facto used (in kg/week), the R^2 value is reduced from $R^2 = 0.81$ to $R^2 = 0.73$. The latter may still be interpreted as a high degree of linear correlation between observed and predicted values. After recalculation of the values, particularly two data tuples appear to deviate from the linear regression line in the lower diagram (i.e., the data tuples (869 | 2,036) and (2,633 | 3,463)). If these two weekly values would be removed from the evaluation, R^2 would increase from 0.73 to 0.78. This illustrates the sensitivity of the results to individual deviating values. The highest difference between the observed and predicted values was observed for the data tuple (869 | 2,036) discussed before, with a difference between the observation and prediction of 1,167.35 kg ACH/week. It was not possible to determine reasons for the deviations of these individual data tuples based on the quantitative data base. In summary, it can be concluded that the multiple regression model established in Chapter 4.4 provides a good estimation of coagulant use at the DWTP of Malaba-Tororo.

Figure 49 illustrates the correlation between observed and predicted values of weekly coagulant use including all case study DWTPs. As before, the upper diagram shows the linearised values in natural logarithmic form, while the lower shows the values after recalculation to the coagulant quantities that were de facto used (in kg/week). Both diagrams show trend lines, corresponding functional equations, and R^2 values for the overall multiple regression model, as well as the individual correlations for each case study DWTP. After recalculating the values, the overall R^2 value is reduced from $R^2 = 0.94$ to $R^2 = 0.83$. The latter still indicates a high degree of linear correlation between observed and predicted values for the overall model. The specific correlation for the DWTP of Sono remains roughly the same after recalculation, while the correlation is improved from $R^2 = 0.45$ to $R^2 = 0.55$ for Lirima, and impaired from $R^2 = 0.76$ to $R^2 = 0.65$ for Malaba-Tororo. In general, both diagrams illustrate well that Lirima mainly covers smaller observations, closely followed by Sono. For Malaba-Tororo, numbers and value range are comparatively high, which goes in line with the observations discussed for Figure 31. After recalculation of the values, several data tuples appear to deviate from the overall linear regression line in the lower diagram, particularly for Malaba-Tororo (e.g., the data tuples (2,633 | 7,130), (5,652 | 7,737), (6,397 | 9,436), (7,979 | 9,667), and (9,791 | 5,865)). The highest difference between observed and predicted values was observed for the data tuple (2,633 | 7,130), with a difference between the observation and prediction of 4,496 kg alum eq./week. If the five weekly values listed above would be removed from the evaluation, R^2 would increase from 0.83 to 0.88. This illustrates the sensitivity of the results to individual deviating values. Three of the five weekly values listed above were calculated based on turbidity outliers, which suggests that the multiple regression model may have weaknesses in calculating coagulant use values for high raw water turbidities. However, the largest deviation of 4,496 kg alum eq./week came about with regular input values without any outlier. Overall, it was not possible to clearly determine reasons for the deviations of the data tuples listed above based on the quantitative data base. In summary, it can be concluded that the multiple regression model established in Chapter 4.4 provides a very good estimation of coagulant use at the case study DWTPs.

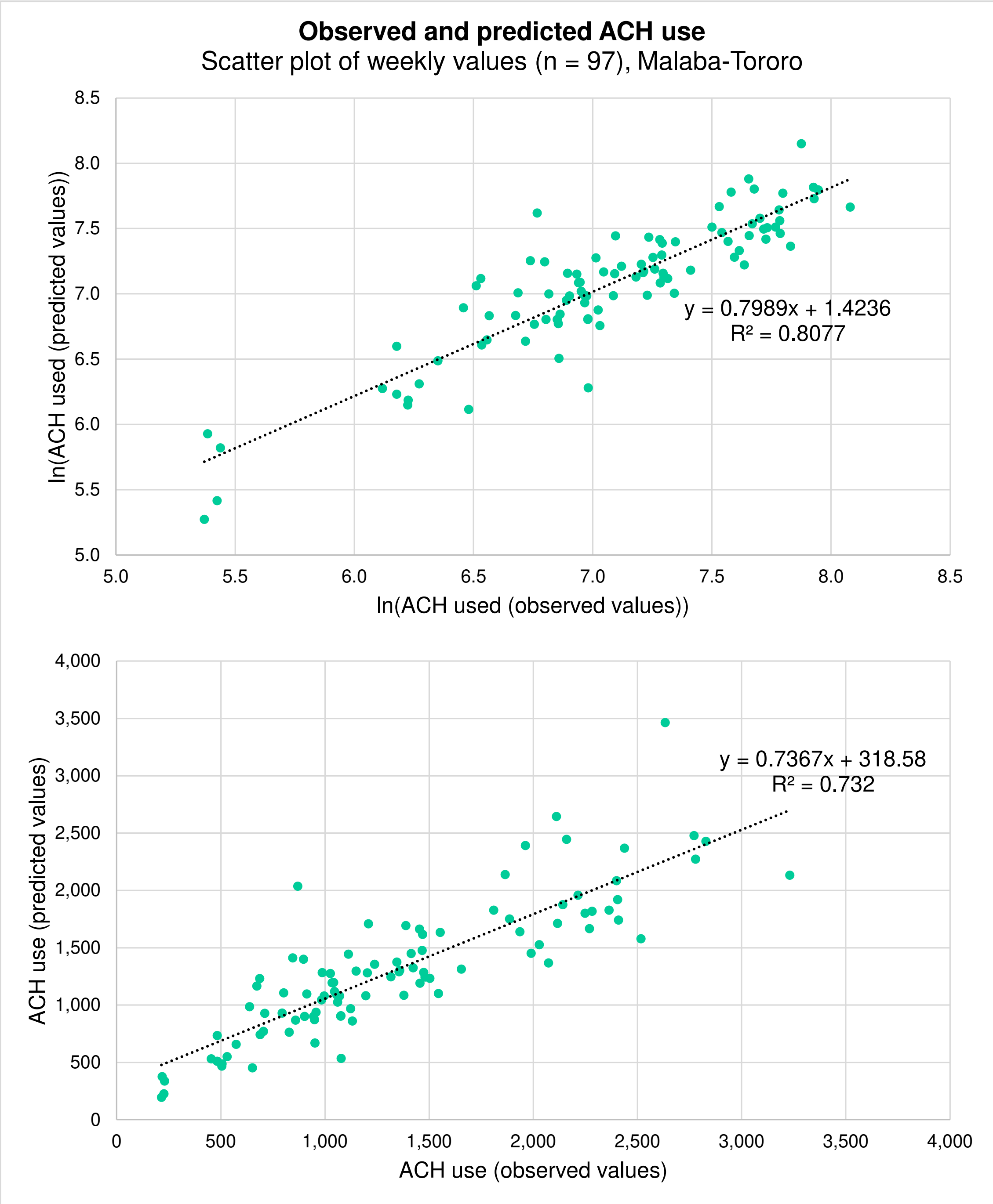


Figure 48: Correlation between observed and predicted coagulant use values for the DWTP of Malaba-Tororo, based on the multiple regression modelling approach established in Chapter 4.4. The upper diagram shows the relationship for the linearised values, the lower for the values without linearisation. Furthermore, the trend lines and their corresponding functional equations and R^2 values are shown.

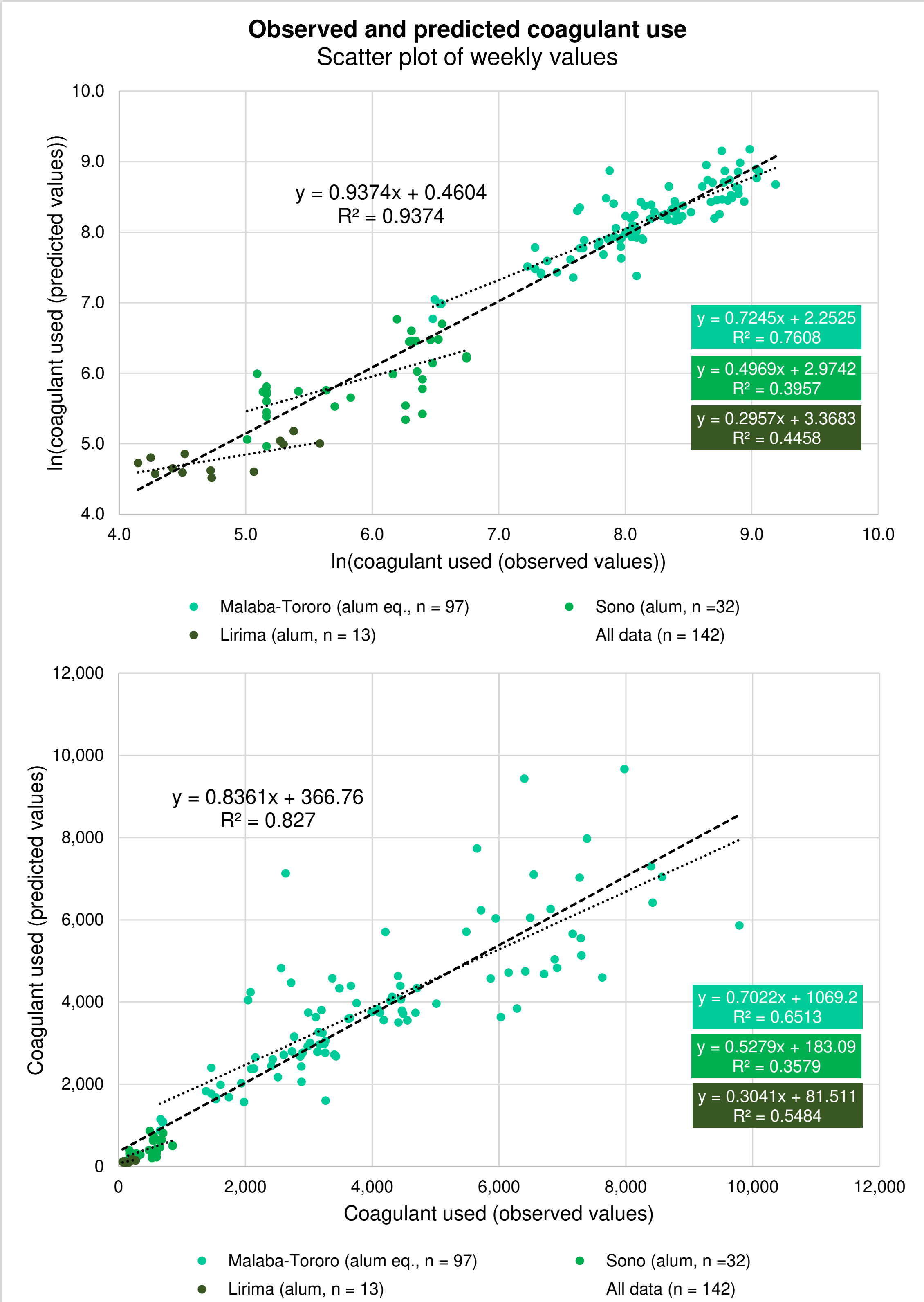


Figure 49: Correlation between observed and predicted coagulant use values for the case study DWTPs, based on the multiple regression modelling approach established in Chapter 4.4. The upper diagram shows the relationship for the linearised values, the lower for the values without linearisation. Furthermore, the trend lines and their corresponding functional equations and R^2 values are shown.

5. Conclusions and recommendations

5.1. General conclusions

The water quality of streams in the SMMRB is subject to pronounced variations. Particle-related parameters such as apparent colour and turbidity vary considerably depending on the season and the respective location within the river basin. At the intake points of public surface water treatment plants, the associated polluting constituents are taken up with the stream water and treated in water purification processes. Since conventional water treatment systems are predominant within the SMMRB, increased sediment and particle contents particularly affect the treatment stages coagulation, flocculation, sedimentation, and filtration. The corresponding variable input factors are, besides treatment time, coagulant chemical use, and energy consumption which is associated with backwash water volumes. Due to these relationships, impaired intake water quality represented by increasing turbidity leads to an increase in treatment effort represented by the input factors mentioned before. Furthermore, disinfectant chemical use is a variable input factor at a conventional DWTP. As the disinfection stage is located after filtration, it is though not affected by raw water turbidity.

To investigate the depicted relationship, three case study DWTPs in the SMMRB, namely Lirima, Sono, and Malaba-Tororo, were considered in this thesis. As they are all located in the Ugandan part of the SMMRB, the data base for the present thesis was mainly provided by the Ugandan public utility responsible for municipal water supply in the country, NWSC. To answer the research questions, several parameters from the quantitative data base were analysed with regards to precipitation, raw water quality, and operating parameters for the observation period September 2016 to January 2020. Besides the mentioned raw water quality parameters, operating parameters were analysed regarding processed water volumes (i.e., raw water pumped, final water produced, service water), treatment chemical use (i.e., coagulant use, disinfectant use), and energy consumption. Overall, the data analysis and interpretation carried out in the present thesis confirmed the depicted relationships. Furthermore, a statistical estimation for the impact of surface water quality variations on treatment effort was derived.

Research question I:

Which of the considered raw water quality and operating parameters show characteristic differences in magnitude in

a. *the dry and rainy season, and*

b. *between DWTPs located more upstream and more downstream along the streams in the river basin?*

The parameters mentioned before were evaluated in Chapter 4.2 separately according to season and case study DWTP. As defined in the present thesis, the wet season extends from March to November and the dry season from December to February. Clear seasonal variations were observed for precipitation, raw water apparent colour, raw water turbidity, raw water pumped, final water produced, coagulant use, and coagulant dose rate. No seasonal variations were observed for service water, coagulant to turbidity ratio, and disinfectant use. For energy consumption, the data availability was not sufficient to make any statements in this regard.

As expected, average daily precipitation in the relevant upstream areas of the case study DWTPs increases considerably during the wet season. Depending on the respective plant, about 2-3 times more rainfall can be observed in the wet season compared to the dry season. The precipitation time series show clearly pronounced temporal variations and distinct annual peaks in April/May and October. However, uneven temporal precipitation patterns were observed during the observation period, with higher yearly values in 2019 compared to 2017 and 2018. Like precipitation, also the parameters related to water quality and coagulant chemicals show higher values in the wet season compared to the dry season. For example, average turbidities at the intake water of Malaba-Tororo were at 572.93 NTU in the wet season and 110.59 NTU in the dry season. A similar picture is observed for raw water apparent colour. This implies that stream water quality in the SMMRB is better during the dry season months and considerably deteriorated in the wet season. As a response, average coagulant chemical uses and dose rates applied at the case study DWTPs are unanimously higher in the wet season than in the dry season. At most considered DWTPs, the dose rates are roughly twice as high in the wet season. In contrast, the water volume parameters were largely higher during the dry season and lower during the wet season compared to the overall mean. This might be due to increased water demands by different users in the respective supply areas during the dry season, when precipitation is decreased, and hence more water is required for agricultural irrigation and other uses.

Regarding DWTPs located more upstream and more downstream along the streams in the river basin, clear variations could be observed for raw water apparent colour, raw water turbidity, coagulant use, coagulant dose rate, disinfectant use, and disinfectant dose rate. No variations could be observed for precipitation and coagulant to turbidity ratio. For energy consumption and service water, the data availability was not sufficient to make specific statements in this regard. However, it appears likely that the two parameters increase the more downstream the DWTP is located within the SMMRB. Average raw water pumped, and final water produced show differences between the DWTPs in line with the respective plant capacities, i.e., increase from Sono via Lirima to Malaba-Tororo. Yet, no trends regarding the plant's location along the source stream were observed for the water volumes.

As expected, both particle-related water quality parameters, apparent colour and turbidity, increase from Lirima via Sono to Malaba-Tororo, i.e., increase the more downstream the DWTP is located within the SMMRB. The relative differences between the three DWTPs are clearly pronounced, regardless of the season. For example, Lirima shows a mean raw water turbidity of 17.00 NTU, while Sono's mean value of 31.58 NTU is roughly twice as high. Malaba-Tororo has a mean turbidity of 488.93 NTU, which is about 29 times the value of Lirima, and 15 times the value of Sono. The relative differences are even more pronounced for raw water apparent colour, though the data availability is limited for Lirima and Sono. The findings imply that stream water quality in the SMMRB deteriorates from the stream's sources to their respective outlets. As a response, average coagulant chemical uses and dose rates applied for water treatment increase from Lirima via Sono to Malaba-Tororo, i.e., increase the more downstream the DWTP is located within the SMMRB. While Lirima shows a mean alum dose rate of 7.00 mg alum/L after outlier analysis, Sono's value of 19.03 mg alum/L is 2.7 times as high. At Malaba-Tororo, 39.85 mg ACH/L are used, which equals to an estimated 120.75 mg alum/L. This would be 17 times the value of Lirima, and six times the value of Sono. Similar observations are made for coagulant use.

<u>Research question II:</u>

To what extent are precipitation, raw water quality, and treatment effort correlated at the case study DWTPs?

Selected parameters related to precipitation, raw water quality, and variable treatment effort were evaluated in time series diagrams and simple regression analyses in Chapter 4.3. From the time series, it appears that the established relationships show some degree of correlation, particularly for the data series of Malaba-Tororo. For large parts, raw water turbidity and coagulant dose appear to follow the seasonal course indicated by precipitation. For Lirima and Sono, the observations are not as clear.

The calculated coefficients of determination (R^2) that indicate the strength of correlations varied strongly depending on the respective parameters considered, the temporal resolution, the DWTP, the applied functional form (linear or natural logarithm), and whether outliers were excluded from the analysis or not. Determined R^2 values varied from 0.00, indicating no relationship at all, to 0.71, indicating a comparatively high degree of correlation. The latter implies that 71 % of the dependent variable could be explained by the independent variable, while 28.55 % could be explained by other factors. The highest correlations for the respective relationships were observed for "Precipitation → Raw water turbidity" at R^2 = 0.63, for "Precipitation → Coagulant use" at R^2 = 0.50, for "Precipitation → Coagulant dose rate" at R^2 = 0.45, for "Raw water turbidity → Coagulant use" at R^2 = 0.71, and for "Raw water turbidity → Coagulant dose rate" at R^2 = 0.66. All these R^2 values imply moderate to high degrees of correlation. The highest value of 0.71 mentioned before was observed for the relationship of raw water turbidity to coagulant use in natural logarithmic form and weekly resolution at Malaba-Tororo. The lowest correlations determined for the respective relationships were all below R^2 = 0.003. The distinct differences between the highest and lowest calculated R^2 values illustrate the significance of the boundary conditions on the calculated correlation. In general, higher correlations were observed for coarser temporal resolutions (e.g., weekly input data resulted in higher correlations than daily input data if any other boundary condition was kept equal). The highest R^2 values calculated based on daily, weekly, and monthly data resolutions were R^2 = 0.56, R^2= 0.71, and R^2 = 0.63, respectively. Furthermore, the correlations at the DWTP of Malaba-Tororo located most downstream within the SMMRB were observed to be higher than at Sono, while Sono showed generally higher correlations than Lirima. In fact, four out of the five highest R^2 values listed above were observed at Malaba-Tororo, two for monthly and two for weekly temporal resolution of input data. The highest R^2 values calculated for Lirima and Sono were R^2 = 0.55 and R^2 = 0.45, respectively. Almost all calculated correlations indicate a positive slope of the corresponding functional equation, i.e., a proportional relationship, while some unexpectedly indicate a negative slope, i.e., a reciprocal relationship, especially for the relationship "Precipitation → Raw water turbidity".

<u>Research question III:</u>

How can the impact of precipitation and raw water quality on treatment effort be modelled for the case study DWTPs using multiple regression and considering the available data?

A multiple regression modelling approach was developed in Chapter 4.4 to estimate the impact of raw water quality on treatment effort at the case study DWTPs. The model was established based on the results presented in Chapters 4.1, 4.2, and 4.3, as well as on background knowledge from the literature. Due to limited data availability, the parameters backwash water volume and energy consumption, which were initially intended to be included in the modelling approach, could not be considered. Therefore, the dependent variable to represent the response in treatment effort to varying raw water quality was defined as the coagulant chemical use per week ($Coag_t$). As independent variable to represent intake water quality, raw water turbidity was selected due to better data availability compared to apparent colour, and better comparability of the results with the literature. Furthermore, three control variables were included to control for factors that may bias parameters of interest. These include raw water pumped (Rwp_t), precipitation ($Rain_t$), and seasonality ($Season_t$). Detailed information on the choice of explanatory variables is provided in Chapter 3.4.4. The final equation for the univariate multiple regression model is shown in Equation (10).

$$\ln(\boldsymbol{Coag_t}) = \beta_0 + \beta_S \times \ln(Season_t) + \beta_R \times \ln(Rain_t) + \beta_{Rwp} \times \ln(Rwp_t) + \boldsymbol{\beta_{WQ}} \times \ln(Turb_t) + \varepsilon_t \quad (10)$$

To include all case study DWTPs in the multiple regression model, the above equation was further expanded by introducing two 0-1 dummy variables (dv) for Sono and Malaba-Tororo. Lirima was used as a reference and hence did not require a dv. For the evaluation, coagulant use at Malaba-Tororo was considered as an estimated alum equivalent use. The expanded multiple regression equation is shown in Equation (11).

$$\ln(\boldsymbol{Coag_t}) = \beta_0 + \beta_S \times \ln(Season_t) + \beta_R \times \ln(Rain_t) + \beta_{Rwp} \times \ln(Rwp_t) + \boldsymbol{\beta_{WQ}} \times \ln(Turb_t) + \beta_{DWTP2} \times dv_{Sono} + \beta_{DWTP3} \times dv_{Malaba-Tororo} + \varepsilon_t \quad (11)$$

For the subsequent calculation, a weekly temporal resolution of input data and the Ordinary Least Squares (OLS) estimator were selected.

Research question IV:

What are the turbidity elasticities for the selected water supply schemes for the observation period, i.e., the percentage change in treatment effort resulting from a 1 % change in source water quality (after Price and Heberling 2018, p. 199)?

The multiple regression model established before was run using all available empirical data on precipitation, raw water quality, and treatment effort, in weekly resolution. The results are provided in Chapter 4.5. First, Equation (10) was calculated for Malaba-Tororo alone, since the DWTP shows the best data availability and reliability, the most stable operation during the observation period, and the most accurate coagulant dosing procedure of the case study DWTPs. Thereby, the impact of water quality variations on chemical treatment effort was estimated for a water supply system located downstream within the SMMRB. The evaluation delivered a statistically significant water-quality elasticity (i.e., turbidity elasticity) of 0.358. This implies that a 1 % decrease in stream water turbidity leads to a 0.358 % reduction in coagulant chemical use at sample averages.

The evaluation for all three case study DWTPs according to Equation (11) delivered a statistically significant water-quality elasticity of 0.389, implying that a 1 % decrease in stream water turbidity leads to a 0.389 % reduction in treatment effort in average over the three DWTPs. The elasticity is close to the value of 0.358 calculated for Malaba-Tororo alone, indicating a difference of only 0.031 between the two estimations. Thereby, it can be concluded that the response of the case study DWTPs to varying raw water turbidities, expressed by coagulant chemical use, is comparable.

However, the validity of the results is limited to some extent. According to Dearmont et al. (1998) and Abdul-Rahim and Mohd-Shahwahid (2011), the calculated elasticities are only valid in the neighbourhood of the mean values of the respective influencing parameters. The authors stated that the calculated elasticities should not be considered outside the range of the data used for the calculation. Therefore, the analysis results cannot directly be transferred in case of drastic reductions of raw water turbidity in the SMMRB. Another restriction is mentioned by Price, Heberling (11/8/2017, p. 12), who stated that the elasticities are only relevant for small changes in raw water quality. Particularly at Malaba-Tororo, major fluctuations in raw water quality were observed (see Chapter 4.2.2). Therefore, the results from the multiple regression analyses must be considered with care. Nevertheless, the results clearly show the connection between raw water quality and treatment effort in the case study DWTPs, and potential savings if raw water quality would be improved.

5.2. Practical implications

High turbidity elasticities were calculated for the case study DWTPs in comparison to findings from the literature. This implies that water treatment effort in the river basin is rather sensitive to variations in surface water quality. Even small changes in stream water turbidity may lead to considerable variations in coagulant chemical uses and thereby treatment effort. Based on the estimated turbidity elasticity of η = 0.389 and the weekly input data, average turbidity reductions of 0.28 NTU (Lirima), 0.30 NTU (Sono), and 4.88 NTU (Malaba-Tororo) would lead to annual savings of 27 kg alum (Lirima), 87 kg alum (Sono), and 252 kg aluminium chlorohydrate (ACH, Malaba-Tororo). To put these results into an economic perspective, an estimation was made based on average unit costs mentioned by NWSC staff of 1,383 UGX/kg (0.33 €/kg) for alum and 5,875 UGX/kg (1.39 €/kg) for ACH. Based on these numbers, the reductions resulting from a 1 % decrease in average turbidity would result in mean avoided treatment costs per year of 37,341 UGX (8.87 €, Lirima), 120,321 UGX (28.57 €, Sono), and 1,480,500 UGX (351.48 €, Malaba-Tororo), in case coagulant dosing at the treatment plants would be adjusted accordingly. It is noteworthy that any water quality improvement would lead to the indicated treatment cost savings, which might not necessarily be only 1 %. For example, if average raw water turbidity would be reduced by 10 % or 48.82 NTU at Malaba-Tororo, this would hypothetically decrease treatment costs by 14,805,000 UGX (3,515 €) per year.

To provide some context to these numbers, a preliminary estimation of the total annual costs for treatment chemicals and energy consumption at Malaba-Tororo was made[8]. The results varied between 1,964,172,784 UGX (466,309 €) and 2,265,252,244 UGX (537,787 €) during the observation period. In view of these numbers, the above-mentioned cost reductions due to decreasing raw water turbidity appear rather small. However, they include only effects on coagulant chemical use, and do not consider reductions in energy consumption or any long-term expenditures at the DWTPs. To accurately embed the findings of this thesis into the overall variable treatment effort at the case study DWTPs, closer investigations would be required, as mentioned in Chapter 5.4.

The described quantitative estimations can be considered as the potential incentives for investments in source water protection in the SMMRB. According to Moses Butele, NWSC is already active in source water protection in the river basin, e.g., by planting and maintaining vegetation such as trees and wetlands, which is mainly carried out in

[8] A detailed economic assessment of the impacts of raw water quality variations at the case study DWTPs will be provided by the author in a subsequent study project report.

the upstream areas of the SMMRB. These measures aim at filtering water and protecting riverbanks. Moses Butele further elaborated that the source water protection measures could be enhanced in the future, which would require engagement from all stakeholders, e.g., NWSC, farmers, environmental management agency, local leaders, and international donors.

The presented results provide an initial estimation of potential benefits of source water protection from a water supply point of view. In general, the results show that a reduction of stream water turbidity would decrease the chemical treatment costs in the case study DWTPs. This encourages NWSC's envisaged plans for source water protection in the river basin and calls for efforts to be stepped up even further. The author particularly recommends establishing and monitoring water protection zones in riparian areas of the streams in the SMMRB. Furthermore, improving farming practices by smallholders, e.g., by investments in tools, equipment, or community-based education, appears promising to increase erosion prevention measures in the SMMRB. Another opportunity for NWSC is to take mitigating actions like using reservoir water instead of stream water, and to design such raw water reservoirs in a way that reduces the inflow of sediments (Warziniack et al. 2017, p. 14). This would particularly require an appropriate land management around the reservoirs, which should ideally be treated by the corresponding treatment plant as the first step of the treatment process (Warziniack et al. 2017, p. 14).

The described practical implications from the present study go in line with findings from the literature. Recent research advocates for integrating the safeguarding of source water from contamination through an adjusted land use management as an additional barrier in a multi-barrier approach, and to avoid in-plant treatment costs (Price and Heberling 2020, p. 1). This is also a key element within the EU Water Framework Directive (European Parliament and Council 12/22/2000). Heberling et al. (2015, p. 8741) argued that there is regularly a trade-off between source water protection and water treatment at DWTPs. The authors stated that it might be worth for a water supply utility to invest in natural infrastructure or pollution reduction practices in source watersheds for water supply, i.e., to engage in watershed management, rather than accepting increased efforts for water treatment at one or more DWTPs. According to Warziniack et al. (2017, p. 2), millions of dollars are spent by water utilities every year to protect and improve water sources as part of a multiple barrier approach to ensure the delivery of safe drinking water. The authors indicated that there is a wide range of benefits resulting from the implementation of various protective measures, which are difficult to quantify. Heberling et al. (2015, p. 8755) argued that the treatment effort avoided at one or more individual DWTP(s) alone may not be a reasonable incentive to protect source water quality, given the scale and number of potential polluting activities and sites in a watershed. The authors emphasise that by taking a broader perspective on the benefits from improved water quality, also further incentives become visible which may eventually justify watershed management and conservation. This is underlined by Westling et al. (2020, 1, 7), adding that the value of healthy drinking water for public safety surpasses the treatment efforts at DWTPs. The authors plead not to take a single-sector lens, but to consider the vast variety of contributions of a measure by applying a multi-sector equation and incorporating future trends and their scale and composition, including climate change.

Besides these practical implications regarding source water protection activities, the present thesis also emphasises the requirement for and benefits of comprehensive and well-documented monitoring and evaluation. As Appendix B shows, large parts of the quantitative data base had to be worked through by the author in a tedious and time-consuming process to receive a usable data base, in which frequent error corrections and assumptions were necessary. These lead to several uncertainties of the present study, as described in Chapter 3.5. Improved monitoring and evaluation, including reliable data generation processes, verification of data according to the dual control principle, and automatic checks for consistency and validity in digital data sets, is recommended to improve data availability and reliability. Furthermore, extensive evaluation of the acquired data and derivation of priorities for action are recommended, e.g., with regards to the depicted trade-off between source water protection and water treatment onsite a DWTP. Nevertheless, it is important to stress that the provision of data by NWSC allowed, for the first time in Sub-Saharan Africa, to perform the analysis documented in this thesis. Thus, substantial information was added to the body of knowledge regarding the relationship between source water quality and water treatment efforts in regions not covered until now.

It is also worth noting that dosing decisions based on professional experience and weather conditions as described in Chapter 4.1 may not be precise in a mathematical and chemical sense. It is likely that the applied coagulant doses rarely meet the optimum coagulant dose as determined by jar test experiments. As only twelve individual jar test protocols (from Lirima DWTP) were available to the author, it was not possible to systematically determine potential deviations between de facto and optimal coagulant doses. However, it can be assumed that the current practice decouples raw water quality and chemical use to a certain degree, creating vulnerability to over- and underdosing of coagulant chemicals. It might even be that sometimes, the weather conditions steer coagulant dosing to a greater extent than raw water quality considerations, or that they are the only factor. Therefore, it is conceivable that an optimisation of coagulant dosing might save more coagulant than a slight reduction of turbidity, which is worth further investigation by NWSC. Technical solutions such as live monitoring systems for water quality and software-based prediction of required coagulant doses are available which might remedy the situation. Furthermore, plant-specific jar testing campaigns as suggested by Takić et al. (2019) might allow to derive empirical equations to estimate appropriate coagulant doses. Either way, any improvements in soil and water conservation in the SMMRB would need for a good communication to the responsible treatment plant staff to avoid continued over- or underdosing of coagulant chemicals.

5.3. Limitations of the study

Limitations of the present study stem from the applied research design and methodology, but mainly from uncertainties in the input data.

As the research design in Chapter 1.2 and the conceptual framework in Chapter 2.6 illustrated, several factors that potentially play a role for the effects of raw water quality on treatment effort were not considered in the present thesis. These include any long-term contributions to treatment effort (e.g., infrastructure investments, repairs, maintenance), several variable contributions to treatment effort (e.g., water acquisition and distribution, labour, laboratory materials), constituent sources in the relevant upstream areas of the water intakes (e.g., land use classifications, point sources, erosion rates, sediment load, nutrient load, pesticide load), further water quality measures (e.g., pH, total organic carbon, temperature), considerations for final water quality (e.g., removal efficiencies), and other control variables (e.g., treatment system properties, service population characteristics, retention times, lagged effects). Furthermore, varying treatment efficiencies at the case study DWTPs were not systematically addressed, but only indirectly considered. Because of the mentioned aspects, the results of the present evaluation must be seen as an approximation of reality and are only generalisable to a limited extend.

The limitations in data availability affected both the reliability of the utilised data, as well as the opportunities for designing the multiple regression modelling approach. For the former, missing or unreliable data series repeatedly required data preparations such as error corrections and assumptions. For several parameters, no autonomous data series were available in the data base but had to be calculated based on other data series and assumed conversion factors. A detailed overview of uncertainties generated by the quantitative data base is provided in 3.5. Overall, the amount and frequency of cases in which data preparations were necessary were high and tedious. Regarding the multiple regression modelling, limited data availability caused that the parameters backwash water volume and energy consumption, which were initially intended to be included in the modelling approach, had to be excluded from the analysis. Hereby, the modelling approach was further limited in addition to the aspects mentioned above.

Another limitation of the study is in the different points in time for which data was available at the case study DWTPs, as illustrated in Table 3. While Malaba-Tororo has the most extensive and consistent data series with an acceptable data availability from January 2017 to January 2020, Lirima mainly has data for 2016 and 2017, and Sono from middle of 2018 to January 2020. Therefore, when comparing raw water and operating parameters between the case study DWTPs, systematic errors are created since data from different points in time that was generated under different boundary conditions is compared with each other. These boundary conditions include precipitation, temperature, evapotranspiration, vegetation cover, and others, which vary over time due to the strong influence of seasonality in the SMMRB. This limits the comparability of the results between the case study DWTPs and creates errors in the multiple regression analysis. The same principle applies for supply interruptions and damages at one plant and its supply network (i.e., Sono) during the observation period, which were not systematically compensated at the other DWTPs.

5.4. Suggestions for further research

On the one hand, suggestions for further research can be made that use and develop the results from the present thesis further. The operating parameters primarily evaluated in this work (i.e., coagulant chemical use and processed water volumes) may be embedded into the overall variable treatment effort at the case study DWTPs, adding disinfectant chemical use, energy consumption, and other factors. This would allow the elasticities from the multiple regression model to be interpreted in a more comprehensive context and to assess the significance of the findings in relation to other variable input factors. Furthermore, an economic analysis of the variable treatment costs at the case study DWTPs would be rewarding, as it would improve comparability with the literature largely based on water treatment costs (see Chapter 2.4.3) and make recommendations more tangible for practitioners. For example, expressing the elasticities as avoided treatment costs per percent change in the independent variable would allow to identify incentives and potential scopes for investment in source water protection in the SMMRB. Based on this, several scenarios are conceivable for the SMMRB, e.g., a “best agricultural management practices” scenario to estimate the hypothetical effect of improved farming practices in the study area on the variable treatment effort at the case study DWTPs. The hence avoided treatment costs may be set in relation to the expenditures that would be required to implement the scenario, e.g., by investing in tools, equipment, or community-based education.

On the other hand, suggestions for further research can be made that address key obstacles of the present work. The thesis clearly showed the requirement for improved data availability and quality from the study area. To verify the results, it would be worthwhile to repeat the present research, or a similar approach based on a more comprehensive and reliable data set that does not require as much preparation, error corrections, and assumptions. In the present thesis, parameters such as backwash water volumes and energy consumption had to be excluded from the multiple regression modelling due to limited data availability. If a more reliable data base was utilised, e.g., by performing designated measurement campaigns at multiple case study DWTPs with repeated daily measurements for each parameter, the results promise greater accuracy and reliability. This would also allow to include backwash water volume and/or energy consumption as response variables in the modelling approach, thereby increasing the informative value of the study. Adding further explanatory or response variables is conceivable as well, e.g., regarding labour, repairs and maintenance, water acquisition, and distribution.

Furthermore, it is worth considering increasing the observation period of the present or a similar research approach to assess the influence of the irregular precipitation patterns observed in the period 2017-2019, which was exceptionally wet compared to the long-term mean. Also, the scope of analysed DWTPs may be expanded to the whole SMMRB, including the DWTPs in neighbouring Kenya. By investigating the impact of stream water quality variations on all surface water treatment systems in the river basin, including on the Kenyan side, potential incentives for source water protection measures in the SMMRB could be evaluated comprehensively.

Regarding the multiple regression modelling approach, the applied model estimators and functional forms may be subject for further research. While in the present research the commonly used OLS estimator and a log-linear transformation were applied due widespread application in the literature, other possibilities exist which might fit even better to the characteristics of the input data. Price and Heberling (2018, p. 199) reported of studies that addressed biased variances and subsequent issues with inference, associated with heteroskedasticity and autocorrelation, by using specific estimators. Also, explorations of polynomial, trans-log, and semi-log specifications may improve the results of the model estimation. Finally, it is worth considering establishing a multivariate model based on the univariate approach present in this thesis, e.g., by including further response variables, or by creating a two-step model with both a landscape characteristics-stream water turbidity equation, and a stream water turbidity-treatment effort equation, linking the two in a recursive manner.

Regardless of the specific focus, it is recommended to perform future research activities in close collaboration with responsible people and experts on the ground. This allows not only for the uptake of the research results, but also improves the research itself since the experience and knowledge of responsible persons, in our case committed plant overseers, is of high value.

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Declaration of academic honesty

I hereby declare that I have composed the enclosed scientific report entirely on my own and that I did not use any outside sources without declaration in the text.

Munich, 16.05.2021, D. Mondorf

Place, date, signature

Appendices

Appendix A: Data collection and detailed description

Data collection

The data used for the present thesis was largely collected during a research stay in Uganda and Kenya from 25th January to 8th February 2020. The overall travel plan, including frequent commuting between Kampala and the study area, was designed together with the CapNex project team, and intended to allow participation in every of the three stakeholder workshops that took place on 27th and 31st January as well as 6th February. In the interim times, different activities in the study area were performed. Arrangements for field strips and site visits were predominantly made in cooperation with the NWSC Tororo Area Office (address: Plot 44/48, Uhuru Drive, P.O. Box 889, Tororo, Uganda). Overall support for the research was granted on 28th January by Fred Businge (Area Manager, Tororo Area, NWSC), who appointed John Ogire (Senior Water Quality Officer, Tororo Area, NWSC) as responsible for supervision of the research undertaking. From then on, John Ogire functioned as the main contact person in the study area. A list of relevant contacts for the research is provided below.

During the research stay, the case study DWTPs on the Ugandan side of the SMMRB (see Chapter 3.1) and their respective water intakes were visited. John Ogire and other NWSC staff members enabled access, guided over the treatment plants, shared relevant information, and took part in expert interviews. During the site visits, notes were taken in handwritten form while position coordinates were captured digitally. In addition, photos and videos were taken by the author (342 photos, 28 videos) and by photographer Elias Okemer (360 photos, 19 videos) who was present during most of the site visits. Furthermore, quantitative data on water quality and operating parameters for the three selected DWTPs was provided by NWSC in hard copy and digital form. From original record books and invoices, photocopies were made by Elias Okemer in his copy shop “Photo berry” in Tororo, adding up to 956 DIN A4 pages (see Chapter 3.3).

Main programme points of the research stay included:

- 27th January 2020: CapNex dissemination workshop at 12 Pearls Hotel, Busia, Uganda, with CapNex team members from Uganda and Kenya. A report summarising the workshop is available on the CapNex website (see CapNex 2020).

- 29th January 2020: Site visit to the water intake of Malaba-Tororo Water Supply with Job Bogere and Moses Paul Eboko.

- 31st January 2020: CapNex policy dialogue workshop at Makerere University, Kampala, Uganda, with CapNex team members from Uganda and Kenya as well as project coordinators Dr. Jakob Lederer and Dr. Mathew Herrnegger. A report summarising the workshop is available on the website of the College of Agricultural & Environmental Sciences, Makerere University (see Anyango 2020).

- 3rd February 2020: Site visits to Lirima Gravity Supply Scheme and Sono Gravity Supply Scheme with John Ogire, Tito Amuku (plant overseer Lirima), Sarah Mbabazi (plant overseer Sono), other NWSC staff, and Elias Okemer (photography and documentation).

- 4th February 2020: Site visit to Malaba-Tororo Water Supply and its water intake with John Ogire and Elias Okemer.

- 6th February 2020: CapNex dissemination workshop at Elegant Hotel, Bungoma, Kenya, with CapNex team members from Uganda and Kenya as well as project coordinators Dr. Jakob Lederer and Dr. Mathew Herrnegger. A report summarising the workshop is available on the CapNex website (see Chasia and Omonge 2020).

In addition to the mentioned site visits on the Ugandan side of the SMMRB, two more DWTPs on the Kenyan side were visited. These included Kimilili Treatment Works in Kapsokwony, operated by Lake Victoria North Water Services Board, on 6th February, as well as Mundika Water Supply in Busia, operated by Busia Water & Sewerage Services Co. Ltd., on 7th February. These additional site visits were conducted to get a more holistic understanding of the drinking water supply in the river basin and to allow for comparability between the approaches on the Ugandan and the Kenyan side. Due to the research design described in Chapter 1.2, these DWTPs were not further considered in the present thesis.

After the depicted research stay, additional information and data was provided by NWSC in cooperation with the department for Water Quality Management and the department for Research & Development. Dr. Irene Nansubuga (Senior Manager, Water Quality Management Department, NWSC) functioned as the main contact person to establish this subsequent cooperation. On 15th April, Christopher Kanyesigye (Manager, Research & Development, NWSC) sent an official letter granting permission to conduct the research together with NWSC. The cooperation was officially commenced on 11th May. Moses Butele (Senior Quality Control Officer in charge of the Eastern Region, NWSC) was appointed responsible for supervision of the research cooperation. Interaction with him took place via telephone calls, emails, and messaging services from 7th May to 5th June, including an expert interview (see Appendix C). From 11th to 15th May, he sent further quantitative data from NWSC's quarterly reporting in digital form (see Table 2, record categories viii and ix). Moreover, remaining questions were discussed with John Ogire from 5th to 22nd June, resulting in another expert interview (see Appendix D).

List of relevant contacts

Name, surname	**Position, institution**
Dr. Mathew Herrnegger	BOKU-project coordinator CapNex, Institute for Hydrology and Water Management (HyWa), University of Natural Resources and Life Sciences, Vienna
Dr. Jakob Lederer	Project coordinator CapNex, Institute for Water Quality, Resource and Waste Management (IWR), Technical University of Vienna, Vienna
Paul Omonge	CapNex team, PhD Candidate, Institute for Hydrology and Water Management (HyWa), University of Natural Resources and Life Sciences, Vienna
Dr. Uwe Hübner	Academic supervisor, Chair of Urban Water Systems Engineering, TU Munich
Emil Bein	Academic supervisor, Chair of Urban Water Systems Engineering, TU Munich
Dr. Irene Nansubuga	Senior Manager, Water Quality Management Department, NWSC
Dr. Mohammed Babu	Research & Development, NWSC HQ, NWSC
Christopher Kanyesigye	Manager, Research & Development, NWSC HQ, NWSC
Fred Businge	Area Manager, Tororo Area, NWSC
John Ogire	Senior Water Quality Officer, Tororo Area, NWSC
Moses Butele	Senior Quality Control Officer in charge of the Eastern Region, NWSC
Tito Amuku	Plant overseer/quality control officer, Lirima Gravity Supply Scheme, NWSC
Sarah Mbabazi	Plant overseer/quality control officer, Sono Gravity Supply Scheme, NWSC
Job Bogere	Plant operator, Malaba Waterworks
Moses Paul Eboko	Plant operator, Malaba Waterworks

Name, surname	Position, institution
Arima Zubair Isa	Branch Manager Kwapa, NWSC
Jesse Nathan Kalange	Arrangements and general support
Elias Okemer	Photography and documentation

Table 7: List of relevant contact persons involved in the present research.

Detailed data description

Quantitative data provided by NWSC in hard copy form

The following quantitative data was provided by NWSC in hard copy form, as summarised in Table 2. The data was grouped by the author into the following seven categories.

i. Record books on daily water quality analyses for Lirima and Sono DWTPs (7 record books, 498 pages in total):

The books include handwritten daily values for total alkalinity (mg/L as $CaCO_3$), residual aluminium (mg/L as $CaCO_3$), free chlorine (mg/L), total residual chlorine (mg/L), colour (PtCo), electrical conductivity (µS/cm), total hardness (mg/L as $CaCO_3$), pH (-), and turbidity (NTU). Water samples (grab samples) for the analyses originated from different points in the treatment trains, including raw, clarified, filtered and final water. According to Moses Butele (see Appendix C), grab samples for the analyses were taken daily from the respective sampling points and were analysed by responsible NWSC staff in the on-site laboratories of the respective DWTP. While parameter turbidity is included in every water quality analysis, the other parameters are provided irregularly, depending on the respective DWTP. Furthermore, the Ugandan national drinking water quality standards are indicated on each sheet. In a few cases, two analyses per day (morning and evening) were performed. The records provide no continuous time series but contain regular data gaps with durations between one day to multiple weeks. The following record books were acquired:

- Lirima DWTP: Four record books titled "Physico Chemical Result Book", one for 29th November 2017 to 12th March 2018 (100 pages), one for 19th March to 28th July 2018 (70 pages), one for 1st September to 22nd November 2018 (36 pages), and one for 1st January to 31st April 2019 (23 pages).
- Sono DWTP: Three record books titled "Physico Chemical Result Book", one for 3rd July to 5th December 2018 (88 pages), one for 7th December 2018 to 28th April

2019 (126 pages) and one for 27th September 2019 to 30th January 2020 (55 pages).

ii. Monthly data collections on daily water quality and operating parameters for Malaba-Tororo DWTP (280 pages in total):

Different data sheets ("Physico-Chemical Characteristics", "Daily Chemical Consumption", "Monthly Report on Bacteriological Examination on Water Supply") and summary reports ("Monthly WQM Summary Report") were stapled together into one data collection per month, covering 22 months from January 2017 to November 2018 (except February 2018). For December 2018 and January 2019, only handwritten summary notes exist.

The data sheets "Physico-Chemical Characteristics" include handwritten daily water quality analysis results for pH (-), apparent colour (pt), turbidity (NTU), total alkalinity (mg/L), total hardness (mg/), total iron (mg/L), free residual chlorine (mg/L), total residual chlorine (mg/L), and residual aluminium (mg/L). Water samples for the analyses originated from different points in the treatment trains, including raw water, clarified water (old and new line), filtered water (old and new line), and final water (old and new line). According to Moses Butele (see Appendix C), grab samples for the analyses were taken daily from the respective sampling points and were analysed by responsible NWSC staff in the on-site laboratory of the DWTP. While parameter turbidity is available for every day, the other parameters are provided irregularly. Monthly averages as well as minimum and maximum values are included for the captured parameters.

The data sheets "Daily Chemical Consumption" include handwritten notes by responsible NWSC staff with daily values for total raw water (m^3/d), total final water (m^3/d), service water (m^3/d), alum used (kg), ACH used (kg), and chlorine HTH used (kg). Monthly sums and averages are included for the captured parameters.

The data sheets "Monthly Report on Bacteriological Examination on Water Supply" include handwritten results of bacteriological and physico-chemical water quality analyses for individual dates. The analyses were performed for E. coli (CFU/100 mL), faecal coliforms (CFU/100 mL), free residual chlorine (mg/L), total residual chlorine (mg/L), pH (-), colour (pt), and turbidity (NTU). Water samples for the analyses originated from different points in the treatment train and distribution networks, including raw water, final water (old and new line), reservoirs, service tanks, delivered facilities, and others. According to Moses Butele (see Appendix C), grab samples for the analyses were taken from the respective sampling points and were analysed by responsible NWSC staff in the on-site laboratory of the DWTP. The records provide no continuous time series but deliver results for individual dates at intervals of a few days to more than one week.

The summary sheets "Monthly WQM Summary Report" include monthly sums and averages for the values captioned on the previously mentioned data sheets, as well as other parameters. The summary is subdivided into seven tables, namely "Table 1: Physico-chemical quality", "Table 2: Performance of treatment units (process monitoring)", "Table 3: Chemical consumption and dose rates (mg/L), "Table 4: Number of samples tested", "Table 5: Compliance to Quality: % No of samples meeting the standard", "Table 6: Chemical status in the area stores", and "Table 7: Waste water results from Central Laboratory" (the latter table is not filled out). Table 2 indicates percentages for overall colour, turbidity, and iron removal as well as for the clarification and filtration steps. Table 3 indicates average, minimum, and maximum dose rates for ACH ZetaFloc and chlorine HTH. Table 6 lists the amount of ACH (kg) and chlorine HTH (kg) left in the store at the DWTP. Furthermore, some of the summaries contain monthly water volumes for raw water pumped (m^3/month), treated water (m^3/month), and service water (m^3/month). Several data gaps exist for various parameters and repeatedly, whole tables are left blank.

iii. Evaluation sheets on water quality for Lirima, Sono and Malaba-Tororo DWTPs and their respective distribution networks at individual days (28 pages in total):

The sheets were provided by the Senior Quality Control Officer, Eastern Region (Peter Obol until June 2017; Moses Butele since October 2017). They include water quality analysis results for pH (-), electrical conductivity (µS/cm), apparent colour (PtCo), turbidity (NTU), total suspended solids (mg/L), total alkalinity (mg/L as $CaCO_3$), total hardness (mg/L as $CaCO_3$), total iron (mg/L), residual aluminium (mg/L), free residual chlorine (mg/L), total residual chlorine (mg/L), faecal coliforms (CFU/100 mL), and E-coli (CFU/100 mL). Furthermore, the Ugandan national drinking water quality standards are indicated on each sheet. Water samples for the analyses originated from different points in the treatment trains and distribution networks, including raw and final water, reservoirs, service tanks, public stand posts, delivered facilities, and others. According to Moses Butele (see Appendix C), the grab samples for the analyses were taken once per month from the respective sampling points and brought to the NWSC central lab in Mbale, Mbale District, where they were analysed for verification. Several data gaps exist for various parameters, indicated with "ND" (not determined) or "NR" (not required). Each sheet includes remarks on current water treatment challenges and potential improvement options for service delivery. The following evaluation sheets were acquired:

- Lirima DWTP: “Report on Physio-Chemical Water Quality Analysis” (5 pages), sampling dates 24th January, 27th February, 20th March, 26th April and 20th July 2019.

- Lirima and Sono DWTP: “Report on Physio-Chemical Water Quality Analysis” (3 pages), sampling dates 27th October, 24th November, 18th December 2017. These sheets include analysis results for both DWTPs.

- Sono DWTP: “Report on Physio-Chemical Water Quality Analysis” (5 pages), sampling dates 24th January, 27th February, 20th March, 26th April and 20th July 2019.

- Malaba-Tororo DWTP: “Water quality for selected points in Tororo area”, (15 pages), sampling dates 30th October, 13th December 2016, 24th January, 21st February, 24th March, 7th April, 25th May, 23rd June, 24th October, 28th November, 13th December 2017, 24th October, 28th November, 18th December 2018.

iv. Record books on daily operating parameters for Lirima, Sono and Malaba-Tororo DWTPs (four record books, 110 pages in total):

The books include handwritten notes by responsible NWSC staff with daily values for raw water meter readings (m^3), final water meter readings (m^3), raw water produced (m^3), final water produced (m^3), alum or ACH used (kg), and chlorine HTH used (kg). In many cases, service water / back wash water (m^3/d) and/or chemical concentrations (mg/L) are included as well. Occasionally, monthly sums and averages for different parameters are indicated. Several data gaps exist for various parameters, sometimes with explanatory comments (“Supply off”, “constant reading”, “faulty”, etc.). For specific parameters at single DWTPs, no values were captured at all (e.g., for raw water meter reading and back wash reading at Sono DWTP) or data gaps with durations between one day to multiple weeks exist. The following record books were acquired:

- Lirima DWTP: “Daily Pumpage Register” (32 pages), 18th September 2016 to 1st March 2018.

- Sono DWTP: “Pumpages and Chemical used” (21 pages) for 3rd July 2018 to 2nd February 2020.

- Malaba-Tororo DWTP: Two record books titled “Pumpages and Chemical used”, one for 27th September 2017 to 30th November 2018 (30 pages), and one for 1st December 2018 to 31st January 2020 (27 pages).

v. Evaluation sheets on determination of alum dose rates by jar test experiments for Lirima DWTP (12 pages):

The evaluation sheets include handwritten notes by Tito Amuku, plant overseer at Lirima DWTP, on date and time of the experiment, raw water pH (-), total alkalinity (mg/L as $CaCO_3$), turbidity (NTU), and total hardness (mg/L as $CaCO_3$). Further, they include the intermediate results of the experiments and the optimum alum dose rate (mg/L) derived. The data covers 12 individual experiments between April and July 2018.

vi. Tax invoices of monthly electricity consumption for Malaba-Tororo DWTP, issued by the electricity network operator Umeme (8 pages):

Invoices indicate monthly energy consumption of the DWTP in kWh/KVA and corresponding costs in UGX. The data covers the time periods 16th July to 1st October 2018, 1st May to 1st August 2019, as well as September and November 2019.

vii. Copies from handwritten record book including individual fuel orders for different DWTPs in the Eastern Region, including Lirima, Sono and Malaba-Tororo DWTPs (20 pages):

For multiple days from 2018, 2019 and 2020, petrol or diesel orders from responsible plant overseers are documented, including serial numbers and volumes. A handwritten note by John Ogire indicates the average pump prices of petrol to be at 4,000 UGX/L and of diesel to be at 3,500 UGX/L.

Quantitative data provided by NWSC in digital form

The following quantitative data was received for this thesis in digital form (Excel files). It can be grouped into three categories, as described in the following.

viii. Quarterly reporting for the Eastern Region for 25 DWTPs and five wastewater treatment facilities in the area, including Lirima, Sono and Malaba-Tororo DWTPs (eight Excel files in total):

Each Excel file includes 11 table tabs (“SEWERAGE SAMPLES”, “WATER SAMPLES”, “COLOUR & TRUB EFFICIENCIES”, “WATER IN SUPPLY”, “BACTERIOLOGICAL”, “BOD& TSS COMPLIANCY”, “Physio-chemical (Wastewater)”, “Physio-chemical (Water)”, “Chemical consumption”, “Dose rates”, and “Coagulation graphs”). The tabs provide monthly and quarterly average and sum values for water quality and operating parameters of the respective facilities. Each Excel file covers three months, adding up to 24 months from January 2018 to December 2019. According to Moses Butele (see Appendix C), the values are generally determined based on daily parameters obtained onsite the DWTPs (see Chapter 3.1). In case certain values could not be determined onsite, those values might be analysis results from a one-off grab sample, analysed once per month in the central NWC laboratory in Mbale. According to Moses Butele, it is not possible to directly determine which monthly value is an average or sum value and which is a single analysis result. Values in the cells were mostly typed in manually, cross references or formulas from one table tab to another do not exist. Several data gaps exist for various parameters, indicated with “NA” (not applied at the moment), “ND” (not done), “NR” (not reported), or “NS” (not sampled). For most parameters, values for the same month are provided in parallel in different table tabs, being partially contradicting. Sometimes, monthly parameters show a repeating number pattern including the exact same values as in previous months, which is discussed in further detail in Appendix B.

The table tab “COLOUR & TRUB EFFICIENCIES” includes information on water quality parameters and removal efficiencies for colour and turbidity for the 25 DWTPs. For each DWTP, the total number of samples tested, average raw and final water colour, average raw and final water turbidity, numbers of samples that comply with colour and turbidity standards, and removal efficiencies are indicated. Quarterly average and sum values for the respective DWTPS are included as well.

The table tab “Physio-chemical (Water)” includes information on physico-chemical water quality characteristics of the 25 DWTPs, both for their raw water (source quality) and final water. Parameters include pH (-), electrical conductivity (µS/cm), colour apparent (PtCo), turbidity (NTU), total suspended solids (mg/L), total alkalinity (mg/L), total hardness (mg/L), total iron (mg/L), residual aluminium (mg/L), free residual chlorine (mg/L), and faecal coliforms (CFU/100 mL). Quarterly average and sum values for the respective DWTPS are included as well.

The table tab “Chemical consumption” includes monthly values for chemicals consumed during operation of the 25 DWTPs, including alum used (mg/L and t/month), ACH used (mg/L and t/month), and chlorine HTH used (mg/L and t/month), amongst others. Furthermore, monthly volumes of raw water abstracted (m^3/month) and water treated

(m^3/month) are provided. Quarterly average and sum values for the respective DWTPS are included as well.

The table tab "Dose rates" includes monthly average, minimum, and maximum values for alum dose rate (mg/L), ACH dose rate (mg/l), and chlorine HTH dose rate (mg Cl_2/L). Furthermore, monthly averages for each parameter based on laboratory tests (chlorine demand tests or jar tests) are provided. Quarterly average and sum values for the respective DWTPS are included as well.

The table tab "Coagulation graphs" includes monthly values for chemicals consumed during operation of 10 of the DWTPs, namely alum used (kg/month) and ACH used (kg/month). Furthermore, monthly volumes of raw water abstracted (m^3/month) are provided. Quarterly average and sum values for the respective DWTPS are included as well.

ix. Monthly reporting for 22 DWTPs and five wastewater treatment facilities in the area, including Lirima, Sono and Malaba-Tororo DWTPs (two Excel files):

Each file has 13 table tabs ("Graphs", "Appendix 1-No. of samples", "App 2 Pyhchem Summary", "Appen 3 Doses", "Appendix 4 water & sewage", "Appendix 6-Sewage results", "App 5 Bulk Chem", "Appendix 7 Target compliance", "T3", "Appendix 6 No compliance", "T4.", "T5", and "T6 &7"). The tabs provide monthly and quarterly average and sum values for water quality and operating parameters of the respective facilities. Each Excel file covers one month, available are October and December 2017. Besides their deviant layout and tab names, the basic structure of the Excel files is comparable to the one from the quarterly reporting described above (category i). Also, the approach to determine the values is the same as described for the quarterly reporting. Values in the cells are mostly typed in manually, but cross references and formulas from one table tab to another are used as well. Several data gaps exist for various parameters, indicated with "N/A" (not applicable), "ND" or "n/d" (not done), or with a blank space. For most of the parameters, values for the same month are provided in parallel in different table tabs, being partially contradicting.

The table tab "T4." includes information on the water quality parameters colour and turbidity and their removal efficiencies for the 22 DWTPs. For each DWTP, the total number of samples tested, average raw and final water colour, average raw and final water turbidity, numbers of samples that comply with colour and turbidity standards, and removal efficiencies are indicated.

The table tab "App 2 Phychem Summary" includes information on physico-chemical water quality characteristics of the 22 DWTPs, both for their raw water and final water. Parameters provided are pH (-), electrical conductivity (µS/cm), colour (PtCo), turbidity (NTU), total suspended solids (mg/L), total alkalinity (mg/L as $CaCO_3$), total hardness (mg/L as $CaCO_3$), total iron (mg/L), residual aluminium (mg/L), free residual chlorine (mg/L), and faecal coliforms (CFU/100 mL). Furthermore, the percentage reductions of colour, turbidity and total suspended solids are provided from raw to final water.

The table tab "App 5 Bulk Chem" includes monthly values for chemicals consumed during operation of the 22 DWTPs, including alum used (mg/L and t/month), ACH used (mg/L and t/month), and chlorine HTH used (mg/L and t/month), amongst others. Furthermore, monthly volumes of raw water (m^3/month) and treated water (m^3/month) are provided. Quarterly average values for the respective DWTPS are included as well.

The table tab "Appen 3 Doses" includes monthly minimum, maximum and average values for alum dose rates (mg/L), ACH dose rates (mg/l), and chlorine HTH dose rates (mg Cl_2/L) for 8 DWTPs. The tab provides both "actual/calculated" average values as they were applied on the plant, and average values based on laboratory tests (chlorine demand tests or jar tests).

The table tab "T6 &7" includes monthly values for chemicals consumed during operation of 13 of the DWTPs, namely alum used (t/month), ACH used (t/month), and chlorine HTH used (t/month) as well as the respective dorse rates (mg/L). The tab provides both actual values as they were applied on the plant, and laboratory dose rates.

<u>Quantitative data provided by Dr. Mathew Herrnegger in digital form</u>

- <u>Precipitation data</u> for the relevant upstream catchment areas of five DWTPs in the SMMRB (one Excel file). The preparation, calculation, and aggregation of the data was described in Herrnegger (2020).

The Excel file has five table tabs ("CHIRPS_Ntot_SMMRB_v2_GEE", "CHIRPS_SB", "CHIRPS_WaterIntakes_1981-2019", "CHIRPS_WaterIntakes_2017-2019", and "temp"). It includes time series data on precipitation for 15 sub-catchment areas within the SMMRB. The data originates from the CHIRPS satellite precipitation data base (Funk et al. 2015) and is provided in the Excel file for the period 1st January 1981 to 31st December 2019 in both daily and monthly resolution. Based on the individual data, the precipitation in the relevant upstream areas of five selected DWTPs was calculated. Among these are the case study DWTPs Lirima, Sono (referred to as "Manafwa"), and Malaba-

Tororo (referred to as “Tororo”), as well as two DWTPs not further considered in this thesis, namely Malaba (Kenya) and Busia.

The table tab “CHIRPS_WaterIntakes_2017-2019” includes daily precipitation values (mm/d) from 1st January 1981 to 31st December 2019 for the 15 sub-catchment areas within the SMMRB. Furthermore, it contains preparatory calculations for creating monthly values for the individual DWTPs.

The table tab “CHIRPS satellite precipitation” contains monthly precipitation values (mm/month) from January 1981 to December 2019 for the relevant upstream areas of the five DWTPs. Furthermore, it shows mean values for each month per DWTP, as well as mean values per DWTP for the whole period considered. These mean values are visualised in two time series diagrams and a bar chart. Furthermore, the table tab contains a map of the SMMRB showing the boundaries of the 15 sub-catchment areas.

The table tab “CHIRPS_WaterIntakes_2017-2019” contains largely the same precipitation values and the identical map as the table tab described before. However, the tab puts a focus on the years 2017-2019. Monthly precipitation in these three years is visualised for the five DWTPs in a time series diagram. Another time series diagram shows the monthly deviation from the long-term precipitation mean (1981-2019, defined as 100 %) during these three years.

The table tab “temp” includes background data required for the calculation of the data described previously, including the area (in km^2) of each of the sub-catchments within the SMMRB.

Appendix B: Preparation of quantitative data

Daily values

As described in subsection “Data digitisation and preparation” in Chapter 3.4.2, several modifications were applied by the author to the daily data provided by NWSC in hard copy form. These modifications were performed to address different peculiarities within the original data such as data gaps; unexpected, unintuitive, or unrealistic values; illegible values which could not be properly determined; or other peculiarities, either for single DWTPs or individual record books. The latter included means to deal with long-term assumptions by NWSC staff or to changes in the data generation methodology within the original data. The unmodified daily data after digitisation is contained in the table tabs “HC Data – Lirima (orig.)”, ”HC Data – Sono (orig.)”, and “HC Data – Malaba-Tororo (orig.)” in the author’s Excel file. The modified data series after data preparation are contained in the table tabs “HC Data – Lirima (ed.)”, ”HC Data – Sono (ed.)”, and “HC Data – Malaba-Tororo (ed.)”, for each DWTP, respectively. These edited table tabs were used for any further analyses, as described in the methodology.

In general, the modifications applied to the daily data include filtering, error corrections, additional calculations, as well as individual and systematic assumptions. All modified, adjusted, deleted, and assumed values were provided with comments and/or marked in colour (see colour coding on top of the respective table tabs) in the author’s Excel file. To perform the modifications, certain assumptions had to be made which are explained in the following, as well as in comments in the Excel file.

Data filtering was applied to illegible values which could not be unambiguously determined by the author, i.e., these values were excluded for further analyses. Error corrections were applied to irregular values which objectively contradicted with any previous and/or subsequent values in the data series. These values were assumed to be twisted numbers or missing a decimal point. Figure 50 shows one example for each modification type.

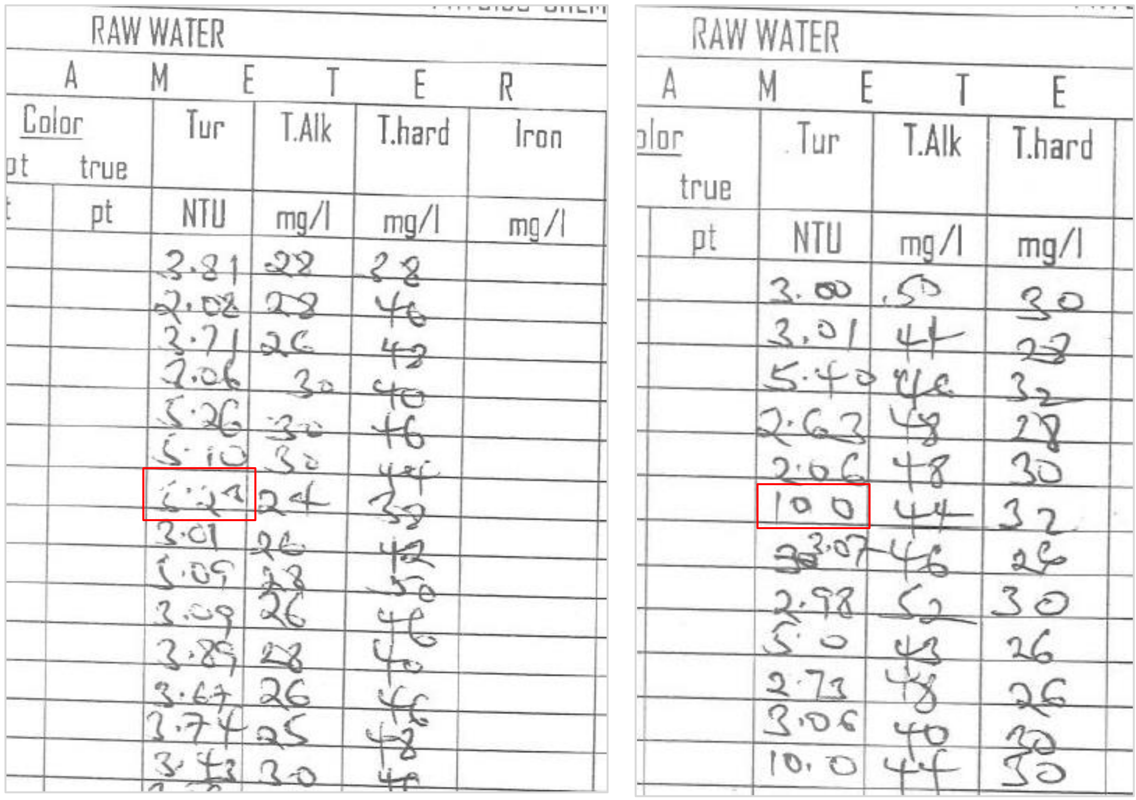
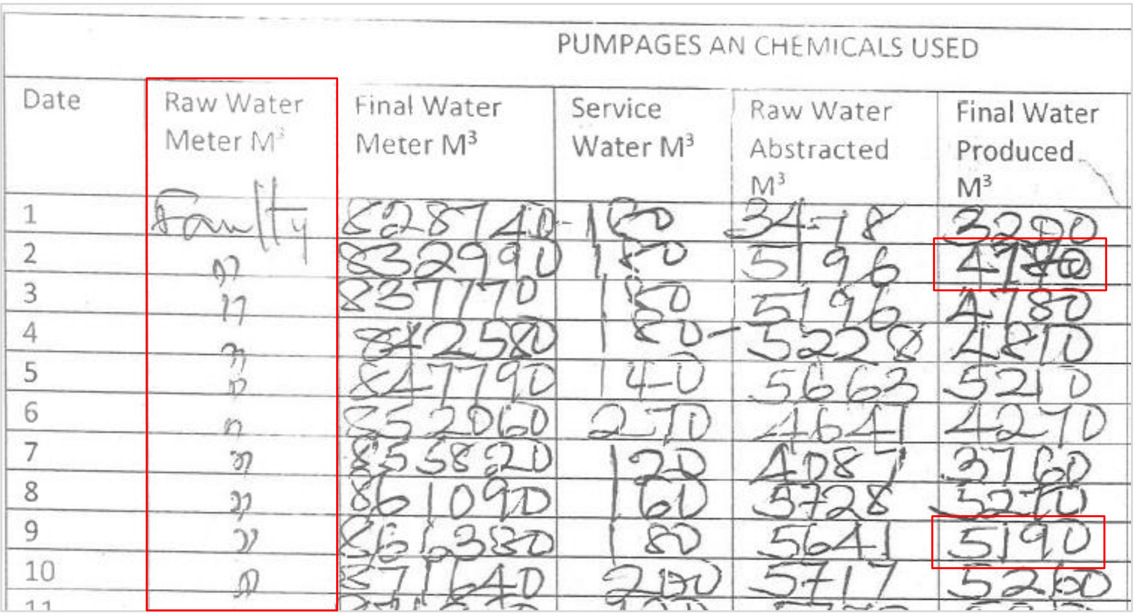


Figure 50: Examples for filtered data (left) and error correction (right). The value marked on the left was illegible and therefore not considered for further analyses. The value marked on the right was determined to be 10.0 NTU, based on the previous and subsequent values. Turbidity values for 7th February 2019 (left) and 6th March 2019 (right), Lirima DWTP.

Further error corrections were applied to the water volume time series from record category iv (see Table 2), i.e., to parameters (3) and (4). In the initial digitisation step, the handwritten values indicated as daily raw, final, or service water in the record books were typed into the Excel file by the author. After calculation of monthly sum and mean values for the respective water volumes, it was observed that the values did not meet the monthly sums indicated in the record books as well. After troubleshooting, it was determined that the monthly sums must have been calculated by NWSC staff based on water volume meter readings, which are provided in the record books as well. When creating the meter reading differences from one month (or day) to the previous month (or day), water volumes identical to the ones specified in the record books could be calculated for most values. Consequently, those values not meeting the meter reading differences were assumed to be faulty values, either due to wrong calculations or due to twisted numbers. To react to this, the error correction performed by the author was to create meter reading differences and thereby correct faulty daily water volume values, until the monthly value indicated in the record book was met. Examples for this modification type are shown in Figure 51.

Besides error corrections, additional calculations were applied to the water volume time series from record category iv (see Table 2) as well. As Table 3 showed, daily water volumes for multiple months were calculated by NWSC staff based on assumptions (indicated in yellow). This procedure was animated by faulty or broken water meters during the respective months. In such cases, missing daily values for raw water were determined from final water values for the same day by multiplication with an estimated conversion factor, and vice versa. The approach was documented on two record sheets (for November 2017 for Lirima and January 2019 for Sono) and was retraced by the author by determination of average ratios between raw and final water for the concerned time series. An example for this approach is shown in Figure 51. Following the same methodological approach, further daily data (indicated in blue in Table 3) was calculated by the author based on estimated conversion factors. The additional raw and final water volumes created by these calculations allowed to further derive dependent parameters such as coagulant dose rate, coagulant to turbidity ratio, and daily chlorine HTH dose rate, using the formulas depicted in Chapter 3.4.2. Overall, the approach allowed for a greater number of daily values within the observation period, thereby increasing the informative value of the sample.

In case error corrections due to conflicting water meter reading differences lead to the creation of revised daily water volumes, the estimated conversion factors were used as well to also revise the respective dependent water volume.



PUMPAGES AN CHEMICALS USED					
Date	Raw Water Meter M³	Final Water Meter M³	Service Water M³	Raw Water Abstracted M³	Final Water Produced M³
1	Faulty	828740	180	3478	3200
2	"	832990	180	5196	4180
3	"	837770	180	5196	4780
4	"	842580	180	5228	4810
5	"	847790	140	5663	5210
6	"	852060	270	4641	4270
7	"	855820	120	4087	3760
8	"	861090	160	5728	5270
9	"	866380	180	5641	5190
10	"	871640	280	5717	5260

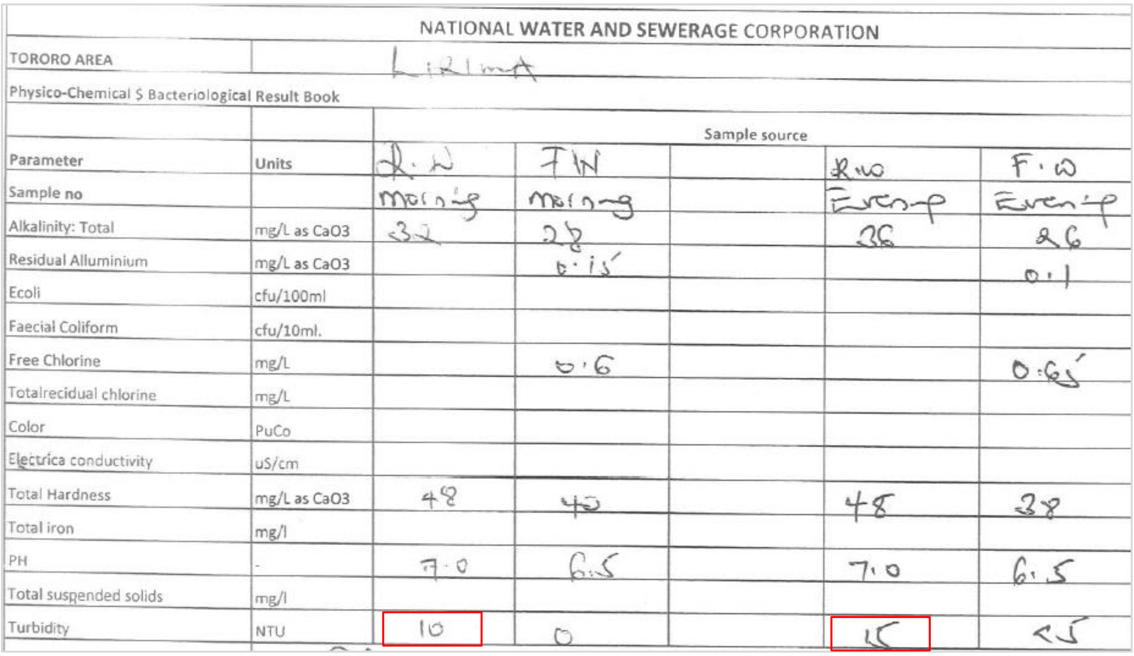
Figure 51: Examples for error corrections and missing water meter readings. The two values marked on the right did not match the meter reading differences indicated in the column “Final Water Meter M³”. As an error correction, the upper value was determined to 4,250 m³ (= 832,990 m³ - 828,740 m³), the lower to 5,290 m³ (= 866,380 m³ - 861,090 m³). The raw water meter readings marked on the left were declared as “Faulty” by NWSC staff. No values were included for the considered period. Based on daily final water volumes and an assumed conversion factor of 1.087, the daily raw water volumes were calculated and included by NWSC staff in the column “Raw Water Abstracted M³”. Pumpages and chemicals used values for December 2019, Malaba-Tororo DWTP.

Other peculiarities, either for single DWTPs or individual record books, were observed as well. For every affected record book, the individual peculiarities as well as the modifications applied by the author to address them are described in the following.

Lirima Gravity Supply Scheme

- “Physico Chemical Result Book”, 19th March to 28th July 2018 (record category i, Table 2):

For several days in March and April 2018, the record book provides two raw water and two final water quality analyses per day, one for “morning” and one for “evening”, respectively. In several cases, this creates two different turbidity values per day. An example is shown in Figure 52. In such cases, to account for both analysis results, the mean value from the two raw water turbidities was considered in the author’s Excel file (see table tab “HC Data - Lirima (ed.)”, column D, cells coloured in blue). For the example shown in the figure, a raw water turbidity value of 12.5 NTU was included for 20th March 2018.



NATIONAL WATER AND SEWERAGE CORPORATION

TORORO AREA	Lirima					
Physico-Chemical $ Bacteriological Result Book						
		Sample source				
Parameter	Units	R.W	F.W		R.W	F.W
Sample no		Morning	Morning		Evening	Evening
Alkalinity: Total	mg/L as CaO3	32	28		36	26
Residual Alluminium	mg/L as CaO3		0.15			0.1
Ecoli	cfu/100ml					
Faecial Coliform	cfu/10ml.					
Free Chlorine	mg/L		0.6			0.65
Totalrecidual chlorine	mg/L					
Color	PuCo					
Electrica conductivity	uS/cm					
Total Hardness	mg/L as CaO3	48	40		48	28
Total iron	mg/l					
PH	-	7.0	6.5		7.0	6.5
Total suspended solids	mg/l					
Turbidity	NTU	10	0		15	<5

Figure 52: Example for a water quality sheet with two analysis results per day, i.e., morning and evening. The marked turbidity values were both considered by the author by using the mean turbidity value for the day. Physico Chemical Result Book, analysis sheet for 20th March 2018, Lirima DWTP.

- “Physico Chemical Result Book”, 1st September to 22nd November 2018 (record category i, Table 2):

For 9th November 2018, two separate water quality analysis sheets are included in the record book, indicating two different raw water turbidity values for the day. To account for both analysis results, the mean value from the two raw water turbidities was considered for that day in the author's Excel file (see table tab "HC Data - Lirima (ed.)", cell D792).

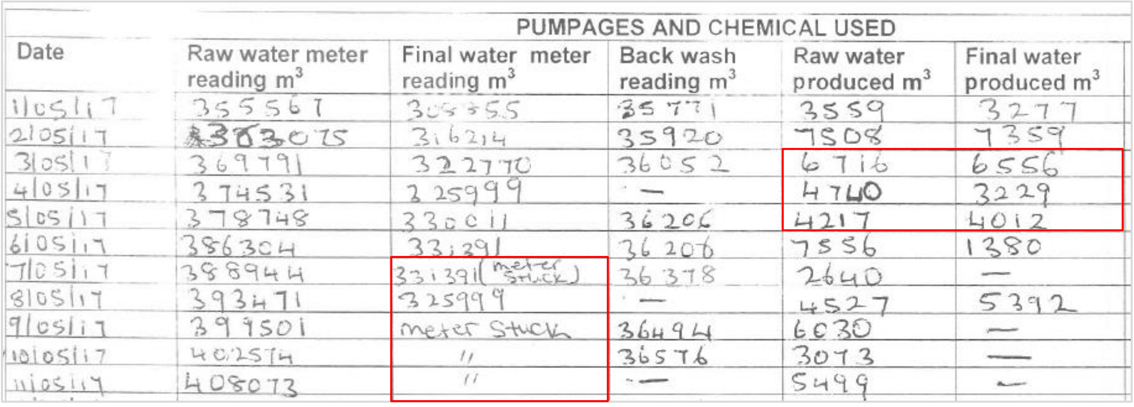
- "Physico Chemical Result Book", 1st January to 31st April 2019 (record category i, Table 2):

Besides daily water quality analyses, the record book provides monthly mean values for alum use and chlorine HTH use (kg/month and kg/d) for January 2019. These were included in appropriate places in the author's Excel file, e.g., in the table tab "HC Summary – Lirima" and used in subsequent calculations.

- "Daily Pumpage Register", 18th September 2016 to 1st March 2018 (record category iv, Table 2):

From 18th September 2016 to 6th May 2017, both the raw and the final water meters generally worked. For this period, values for the parameters (3) raw water pumped and (4) final water produced were first digitised as indicated in the record book, then verified and potentially revised based on the meter reading differences (see table tab "HC Data - Lirima (ed.)", columns E and F, cells coloured in blue). This was done according to the procedure described previously in this chapter. Only on 22nd December 2016, meter readings are missing and a comment states "attendant didn't take readings", which resulted in a data gap.

From 7th May 2017 to 1st March 2019, the final water meter was not or not properly functioning, as indicated by several comments in the record book stating, "meter stuck", "stuck", or "Faulty" (see Figure 53). For this period, the entries for the final water meter include unrealistic and/or incoherent meter readings or blank spaces (see Figure 54). In June 2017, individual final water meter readings are included, but they are incoherent and unrealistic as well. From 14th October 2017 to 1st January 2018, and from 15th February to 1st March 2018, continuous meter readings are included, but imply final water volumes unexpectedly low in comparison to the daily raw water volumes for the same period. It is assumed that the final water meter was faulty or not properly calibrated during all mentioned periods. Therefore, the daily final water values indicated in the record book for were not further considered for the period 7th May 2017 to 1st March 2019.



	PUMPAGES AND CHEMICAL USED				
Date	Raw water meter reading m^3	Final water meter reading m^3	Back wash reading m^3	Raw water produced m^3	Final water produced m^3
1/05/17	355567	[illegible]	35771	3559	3277
2/05/17	363075	316214	35920	7508	7359
3/05/17	369791	322770	36052	6716	6556
4/05/17	374531	325999	—	4740	3229
5/05/17	378748	330011	36206	4217	4012
6/05/17	386304	331391	36206	7556	1380
7/05/17	388944	331391 (meter stuck)	36378	2640	—
8/05/17	393471	325999	—	4527	5392
9/05/17	399501	meter stuck	36494	6030	—
10/05/17	402574	"	36576	3073	—
11/05/17	408073	"	—	5499	—

Figure 53: Comments marked on the left state “meter stuck”, indicating that the final water meter broke. From here on, no reliable final meter readings were included in the record book anymore. The raw and final water values marked on the right were the basis to determine the conversion factor of 0.87 that was indicated by NWSC staff in the record book. Daily Pumpage Register, record sheet May 2017, Lirima DWTP.

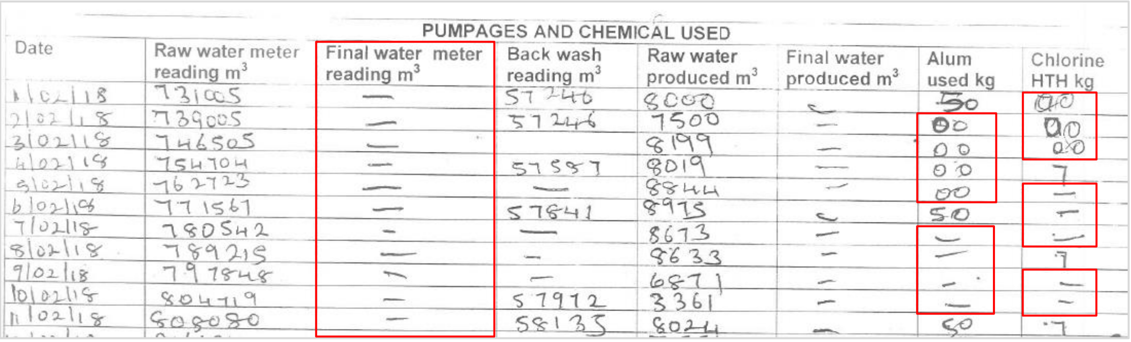
To receive a greater number of values within the observation period, daily values for (4) final water produced were calculated by the author based on measured values for (3) raw water pumped and a conversion factor. For this, the general procedure described previously for this in this chapter was applied. Based on the ratios of final water produced to raw water pumped from 18th September 2016 to 5th May 2017, no predominant conversion factor could be determined by the author (see “Analysis: Calculation of additional final water values”, table tab “HC Data - Lirima (ed.)”, columns N and O in the author’s Excel file). However, a comment by NWSC staff on the record sheet for November 2017 indicates: “Use factor of 0.87 to Calculate Final water”. After closer examination of the data series (see Figure 53), the factor of 0.87 was determined to be the mean ratio of final water produced to raw water pumped from the last three days for which both water meters were in operation (3rd to 5th May 2017), as the following equation shows:

$$\frac{\frac{6{,}556\ m^3}{6{,}716\ m^3}+\frac{3{,}229\ m^3}{4{,}740\ m^3}+\frac{4{,}012\ m^3}{4{,}217\ m^3}}{3} = 0.869595 \approx 0.87 \tag{15}$$

Considering the cited comment by NWSC staff, the conversion factor to calculate final water values based on existing raw water values was defined to be 0.87. In fact, daily final water produced was calculated by NWSC staff using this approach on 1st, 2nd, 3rd, and 9th November 2017. The author expanded this approach to the whole period with faulty final water meter readings from 7th May 2017 to 1st March 2019 (see table tab “HC Data - Lirima (ed.)”, column F, cells coloured in blue), using the following formula:

$$Final\ water\ produced_{day\ i}\left(\frac{m^3}{d}\right) = Raw\ water\ pumped_{day\ i}\left(\frac{m^3}{d}\right) \times 0.87 \tag{16}$$

Regarding parameters (6) alum used and (7) chlorine (HTH) used, continuous daily values are indicated in the record book from 18th September 2016 to 4th January 2017 (alum) and 25th January 2017 (chlorine). From 11th January (alum) and 26th January (chlorine) to 20th June 2017, no daily chemical uses are indicated at all. For these periods, it was hence not possible to include values for Lirima on alum used, alum dose rate, coagulant to turbidity ratio, chlorine use, and chlorine dose rate in the author's Excel file. From 21st June 2017 to 1st March 2018, daily values for alum use and chlorine use are included again, which are though interrupted by various missing values, either indicated with a hyphen ("–"), two zeroes ("00"), or empty cells. Examples are shown in Figure 54.



PUMPAGES AND CHEMICAL USED							
Date	Raw water meter reading m³	Final water meter reading m³	Back wash reading m³	Raw water produced m³	Final water produced m³	Alum used kg	Chlorine HTH kg
1/02/18	731005	–	57246	8000	–	50	00
2/02/18	739005	–	57246	7500	–	00	00
3/02/18	746505	–		8199	–	00	00
4/02/18	754704	–	57587	8019	–	00	7
5/02/18	762723	–	–	8844	–	00	–
6/02/18	771567	–	57841	8975	–	50	–
7/02/18	780542	–	–	8673	–	–	–
8/02/18	789215	–	–	8633	–	–	7
9/02/18	797848	–	–	6871	–	–	–
10/02/18	804719	–	57912	3361	–	–	–
11/02/18	808080	–	58135	8024	–	50	7

Figure 54: Examples for missing final water meter values, as well as interrupted alum and chlorine use data series. The final water meter marked on the left was indicated by NWSC staff as "Faulty" and "stuck". No reliable values were included from 7th May 2017 to 1st March 2019. The data series for alum and chlorine use marked on the right include various data gaps. Daily Pumpage Register, record sheet February 2018, Lirima DWTP.

According to Lirima's plant overseer Tito Amuku, missing daily chemical values are either due to production stops at the DWTP in case of landslides, or due to the fact that the amount of chemical applied to the dosing device on one specific day was sufficient to provide chemicals for the subsequent days as well. Since daily raw water pumped values are present for the whole period covered in the record book, the latter appears to be more accurate for most situations. Therefore, the author assumed days with missing chemical use values as such on which chemicals were continuously applied to the water purification process, but no new chemicals had to be taken from the stock to be added to the chemical dosing device. To depict this concept in the author's Excel file, the amounts of alum or chlorine indicated on any individual day between 21st June 2017 and 1st March 2018 were evenly distributed over the respective day and all following days with missing values (see table tab "HC Data - Lirima (ed.)", columns H and K, cells coloured in blue). For the example shown in Figure 54, this means that alum used was defined to be 10 kg per day from 1st to 10th February 2018, while chlorine HTH use was calculated to 1.75 kg per day from 4th to 7th February and 2.33 kg/d from 8th to 10th February 2018. The adjustment performed in this way also influenced the calculations of daily alum dose rates, coagulant to turbidity ratios, and chlorine dose rates.

Sono Gravity Supply Scheme

- "Pumpages and Chemical used", 3rd July 2018 to 2nd February 2020 (record category iv, Table 2):

The record book generally includes no water meter readings for service water. Therefore, the parameter (5) service water could not be determined for Sono (see Table 3).

Several data gaps from single days up to months exist in the record book, e.g., from 28th to 30th July 2018 (3 days), 4th October to 4th December 2018 (62 days), 29th March to 3rd April 2019 (6 days), or 17th to 22nd October 2019 (6 days). For these interruptions, comments by NWSC staff include statements such as "No supply", "supply is off", or "Supply off due to burst", and no daily operating parameters are provided for the respective periods. Nevertheless, the overall monthly sum and average values are assumed to correspond to reality, since an interruption in the drinking water supply usually results in zero water volumes and chemical uses, regardless of the individual reason. Therefore, no adjustments were made by the author.

Other than that, the record book does not include raw water meter readings. Therefore, parameter (3) raw water pumped could not be directly determined based on existing measurements. While from 3rd July 2018 to 1st January 2019, no daily raw water values were included in the record book, from 2nd January 2019 to 29th January 2020, handwritten daily values were included by NWSC staff (see table tab "HC Data – Sono (ed.)", column E, cells coloured in yellow in the author's Excel file, as well as months indicated in yellow in Table 3). These values must have been created by NWSC staff based on measured daily values for (4) final water produced and a conversion factor. Since a handwritten note on the sheet for January 2019 states "Final water x 1.05", the conversion factor was assumed to be at 1.05. For closer investigation, Figure 55 illustrates the ratio of daily raw water pumped to final water produced values that are indicated in the record book for the period 2nd January 2019 to 29th January 2020. The figure shows that the ratio between the water volumes was at 1.05 was on almost every day within the mentioned period, including only a few exceptions (see "Analysis: Calculation of additional raw water values", table tab "HC Data – Sono (ed.)", columns N and O, end of the table). Thereby, the conversion factor applied by NWSC staff was confirmed to be at 1.05.

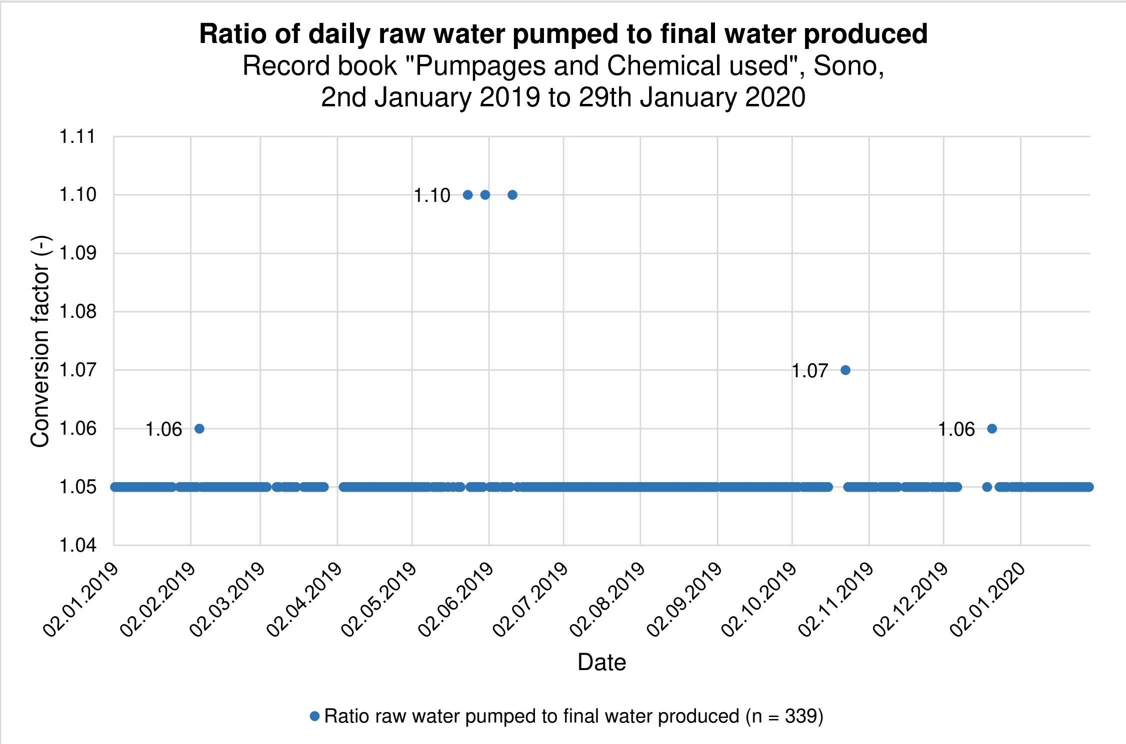


Figure 55: Ratio of daily raw water pumped to final water produced values ("Conversion factor") at Sono for the period 2nd January 2019 to 29th January 2020. The predominantly observed factor of 1.05 was used in 98 % of cases (333 of 339 days). Hence, it was assumed as the conversion factor used by NWSC to calculate daily raw water pumped values based on final water produced values for the DWTP.

In case daily values for final water produced within the period 2nd January 2019 to 29th January 2020 have been revised by the author due to conflicting meter reading differences, the conversion factor of 1.05 was used to revise the corresponding daily raw water pumped values as well (see table tab "HC Data – Sono (ed.)", column E, cells coloured in blue in the author's Excel file).

To receive a greater number of values within the observation period, the author expanded NWSC's approach for the period 3rd July 2018 to 1st January 2019. Daily values for raw water pumped were calculated based on measured final water produced values and the conversion factor of 1.05 (see table tab "HC Data – Sono (ed.)", column E, cells coloured in blue in the author's Excel file, as well as months indicated in blue in Table 3). For this, the following formula was used:

$$Raw\ water\ pumped_{day\ i}\left(\frac{m^3}{d}\right) = Final\ water\ produced_{day\ i}\left(\frac{m^3}{d}\right) \times 1.05 \qquad (17)$$

Malaba-Tororo Water Supply

- Monthly data collections on daily water quality and operating parameters, January 2017 to January 2019 (except February 2018; record category ii, Table 2):

The monthly data collections for Malaba-Tororo include daily and monthly values for several parameters, of which (3) raw water pumped, (4) final water produced, (5) service water, (6) ACH use, and (7) chlorine HTH use were digitised in the author's Excel file (see table tabs "HC Data - Malaba-Tororo (orig.)" and "HC Data - Malaba-Tororo (ed.)" in the author's Excel file). For February 2018, no summary report exists. For December 2018 and January 2019, no daily values are provided, but handwritten sheets with monthly mean and average values for individual parameters. These were used to verify the daily values indicated in the record book "Pumpages and Chemical used" (1st December 2018 to 31st January 2020) discussed below.

For the period 27th September 2017 to 30th November 2018, daily and monthly values for all mentioned parameters were also provided in the record book "Pumpages and Chemical used" (27th September 2017 to 30th November 2018), which will be further discussed below. Hence, it was possible to compare the two hard copy data sources with each other and to find similarities and contradictions between the two. Regarding the parameters service water, ACH use, and chlorine (HTH) use, most daily values from both sources agreed (see table tab "HC Data - Malaba-Tororo (ed.)", columns H, I, O, cells coloured in green in the author's Excel file). This verified the respective daily values. Only in March 2018, noteworthy differences between the data sources are present for the parameters service water and chlorine (HTH) use. Here, the values from the monthly data collection were used with priority.

For the daily water volume parameters (3) raw water pumped and (4) final water produced, the monthly data collections do not provide any water meter readings. Therefore, it was not possible to verify the data using the water meter differences based on this data source. When comparing daily water volume values from the monthly data collections to values from the record book "Pumpages and Chemical used" (27th September 2017 to 30th November 2018), they matched with each other in most cases. However, a considerable share of daily data for raw water pumped and final water produced within the record book was identified to be contradictory, with several inconsistencies and inaccuracies for the two parameters (more details described below). Since these irregularities could not be resolved, it was decided to use the values from the monthly data collections with priority in the author's Excel file and any further analyses. Only for illegible or missing values (e.g., for February 2018), the record book was used as a data source.

Figure 56 shows the ratio of daily raw water pumped to final water produced from 1st January 2017 to 31st January 2019, before any preparations were made by the author (see table tab "HC Data - Malaba-Tororo (orig.)" in the author's Excel file). The figure illustrates that in the first months of the observed period, the ratio varies irregularly with values between 0.959 and 1.865. From 4th October 2017 to 11th September 2019, a considerable share (70 %) of the daily ratios was determined to be at 1.149. From 23rd August 2018 to end of January 2019, the biggest share (86 %) was determined to be at 1.087. Both periods were analysed for their predominant water volume ratios in an "Analysis: Calculation of additional raw water values" in table tab "HC Data - Malaba-Tororo (orig.)", columns N and O, in the author's Excel file. The prevailing majority of exactly the mentioned water volume ratios in the data series appears too regular to originate from real-world measurement conditions which were captured by functioning and calibrated water meters. Also, water meter readings for raw water pumped were rarely indicated in the two record books "Pumpages and Chemical used" (more details described below). Furthermore, a handwritten note on the record sheet for January 2018 indicates "x 0.87" (the inverse of 1.149). These three factors together led to the conclusion that daily values for (3) raw water pumped were calculated by NWSC staff based on measured values for (4) final water produced and a conversion factor of either 1.149 (4th October 2017 to 11th September 2019) or 1.087 (23rd August 2018 to end of January 2019), respectively (see months indicated in yellow in Table 3). The respective daily values were indicated in yellow in the author's Excel file, table tab "HC Data - Malaba-Tororo (ed.)", column E. In case daily values for final water produced within these periods have been revised by the author due to conflicting meter reading differences, the conversion factors of 1.149 or 1.087 were used to revise the corresponding daily raw water pumped values as well (see table tab "HC Data – Malaba-Tororo (ed.)", column E, cells coloured in blue in the author's Excel file, as well as months indicated in blue in Table 3).

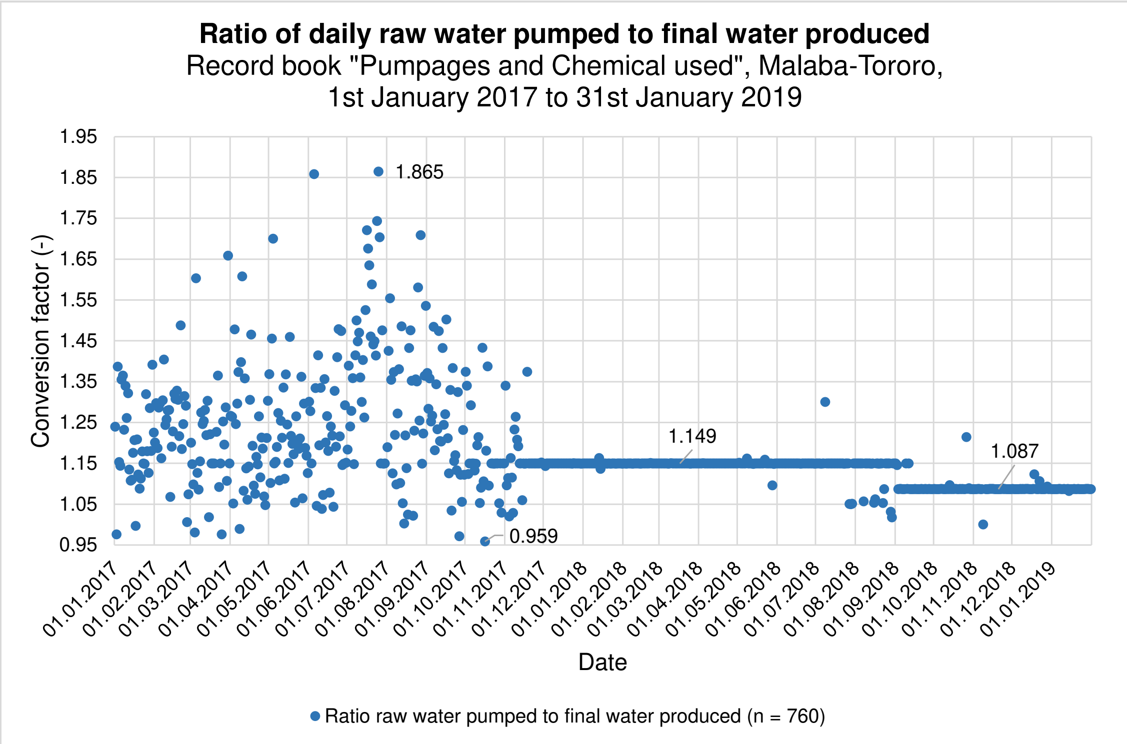


Figure 56: Ratio of daily raw water pumped to final water produced values ("Conversion factor") at Malaba-Tororo for the period 1st January 2017 to 31st January 2019. Values for 1st January 2017 to 30th November 2018 were obtained from the monthly data collections, and for 1st December 2018 to 31st January 2019 from the record book "Pumpages and Chemical used". The ratios are presented before any preparations by the author (see table tab "HC Data - Malaba-Tororo (orig.)" in the author's Excel file).

- <u>"Pumpages and Chemical used", 27th September 2017 to 30th November 2018</u> (record category iv, Table 2):

The record book includes daily values for the parameters (3) raw water pumped, (4) final water produced, (5) service water, (6) ACH use, and (7) chlorine (HTH) which were digitised in the author's Excel file. As daily and monthly values for the same parameters were also provided in the monthly data collections described above, it was possible to compare the two hard copy data sources with each other and to find similarities and contradictions between the two. Regarding the parameters service water, ACH use, and chlorine (HTH) use, most daily values from both sources agreed (see table tab "HC Data - Malaba-Tororo (ed.)", columns H, I, O in the author's Excel file). This verified the respective daily values. Only in March 2018, noteworthy between the data sources are present for the parameter service water and chlorine (HTH). These could not be explained and were not further considered (as described above).

From 27th September to 29th December 2017, the record book generally includes meter readings for both the raw water meter and the final water meter. During that period, several meter readings are missing, e.g., for 1st to 2nd December or 15th to 27th December. A comment on 1st December states "Faulty" for the raw water meter. From 30th December 2017 to 30th November 2018, the record book includes no raw water meter readings at all. Handwritten comments on multiple sheets indicate that the raw water meter was "Faulty". Following the procedure applied for the other record books of record category iv (see Table 2) as well, the daily and monthly water volumes indicated in the record book were verified by creating the meter reading differences from one month (or day) to the previous month (or day). Matching daily values were marked in green in the author's Excel file (table tab "HC Data - Malaba-Tororo (ed.)", column E for raw water pumped and F for final water produced). Unlike observed for the other record books discussed above, the obtained water volumes were largely contradicting the ones specified in the record book. To illustrate this, the calculated daily meter reading differences for final water produced were included in column F in the table tab "HC Data - Malaba-Tororo (orig.)". While cells coloured in green illustrate compliance with the final water values indicated in the record book (column E in the Excel file), yellow values unexpectedly show compliance with the raw water values indicated in the record book (column D in the Excel file). Cells without any colour show no compliance, neither with raw water, nor with final water values. As the "Analysis: Raw and final water values - 28.09.2017 to 30.11.2018" at the bottom of table tab "HC Data - Malaba-Tororo (orig.)" shows, 226 (53 %) of a total of 429 examined daily water meter differences met with the indicated final water values, while 99 (23 %) met with the indicated raw water values and 104 (24 %) with none of the two.

Due to these unexpected results, it could not be unambiguously determined if the calculated final water meter reading differences belong to the final water values, the raw water values, or if another data source was used by NWSC staff to create daily water volumes. To react to this, it was decided that the final water meter reading differences from the record book should be used with priority, as they are likely the most accurate and reliable data source for the parameter (4) final water produced. These meter reading differences were included as daily final water volumes in table tab "HC Data - Malaba-Tororo (ed.)", column F in the author's Excel file. Wherever the calculated values confirmed existing values from the record book, the cells were coloured in green. Wherever they deviated from the existing values, the cells were coloured in blue.

For daily raw water pumped, the meter reading differences were calculated as well, wherever possible (period 27th September to 29th December 2017). When they matched with the daily raw water values indicated in the record book, the corresponding cells were coloured in green (see table tab "HC Data - Malaba-Tororo (ed.)", column E). In case daily final water produced values have been revised by the author due to conflicting meter reading differences, or in case no or no realistic raw water pumped values were included in the record book, the conversion factors of 1.149 or 1.087 mentioned above were used to calculate daily raw water volumes based on existing final water produced values (see table tab “HC Data – Malaba-Tororo (ed.)”, column E, cells coloured in blue in the author’s Excel file).

Besides this, the record book contained daily values for ACH dose rate (mg/L), as determined by NWSC staff. These values were included in the author’s Excel file (table tab “HC Data - Malaba-Tororo (orig.)”, column J) and used as control values to verify the ACH dose rates calculated by the author (column I). As the “Analysis polymer dose rate - control value (record book 27.09.2017 - 30.11.2018)” at the end of the table tab shows, the control values largely confirmed the author’s calculations. 88 % (n = 329) of the calculated daily values met the control values in the record book (rounded to whole numbers). Of 12 % of calculated values that did not meet the control values, 7 % (n = 26) were in a range of a maximum of +/- 2 mg/L higher or lower than the control values, while 5 % (n = 18) showed deviations of more than 2 mg/L. After adjustment of the daily water volumes according to the procedure described above, still 57 % (n = 214) of the calculated ACH dose rates meet the control values indicated in the record book (rounded to whole numbers), while 19 % are in a range of a maximum of +/- 2 mg/L higher or lower than the control values, and 23 % (n = 87) show deviations above 2 mg/L (see “Analysis polymer dose rate - control value (record book 27.09.2017 - 30.11.2018)” at the end of table tab “HC Data - Malaba-Tororo (ed.)”). For any further analyses, the daily ACH dose rates after adjustment of water volumes were used (see table tab “HC Data - Malaba-Tororo (ed.)”, column K in the author’s Excel file).

- “Pumpages and Chemical used”, 1st December 2018 to 31st January 2020 (record category iv, Table 2):

For the whole time covered by the record book, the raw water meter was “Faulty”, as indicated by handwritten comments on every page. Therefore, it was assumed that daily values for (3) raw water pumped were calculated by NWSC staff based on measured values for (4) final water produced and a conversion factor, as described above. Figure 57 shows the observed ratio of daily raw water pumped to final water produced from 1st December 2018 to 31st January 2020, before any preparations by the author. The predominant ratio was determined to be at 1.087 (see “Analysis: Calculation of additional raw water values” at the end of table tab “HC Data - Malaba-Tororo (orig.)” in the author’s Excel file). Therefore, the conversion factor used by NWSC was assumed to be 1.087.

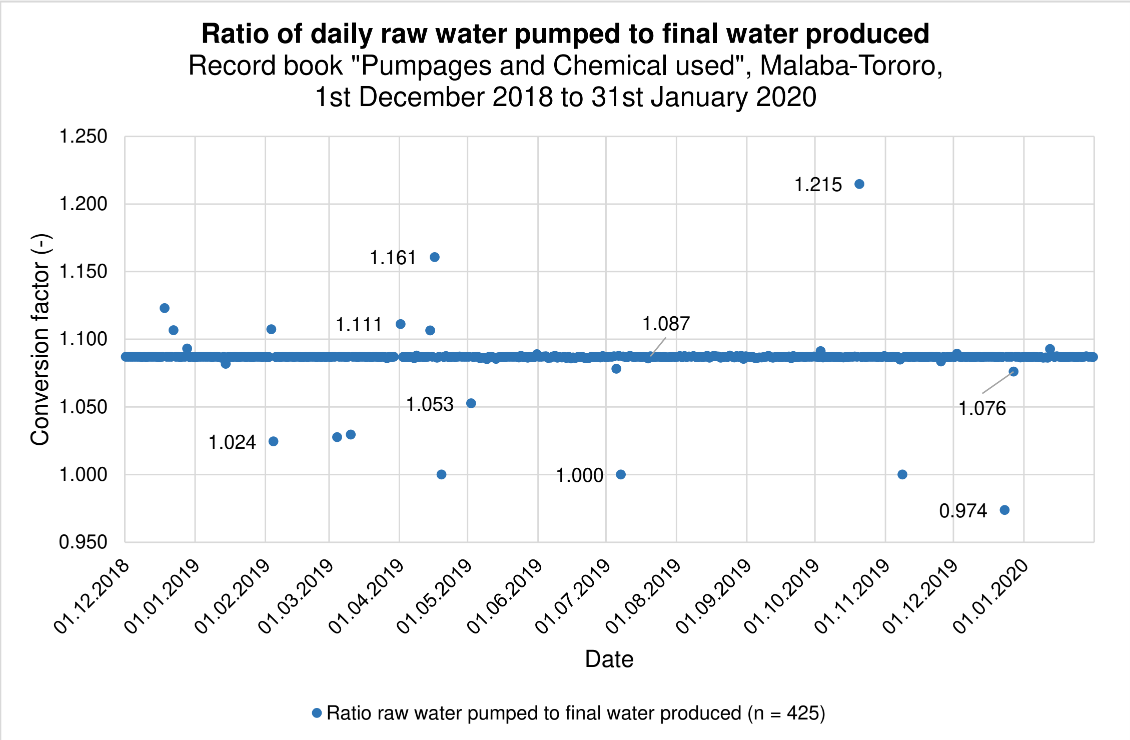


Figure 57: Ratio of daily raw water pumped to final water produced values ("Conversion factor") at Malaba-Tororo for the period 1st December 2018 to 31st January 2020. The ratios are presented before any preparations by the author (see table tab "HC Data - Malaba-Tororo (orig.)" in the author's Excel file). A ratio of 1.087 was used in 82 % of cases (347 of 425 days) and was therefore assumed as the conversion factor used by NWSC.

In case daily values for final water produced were revised by the author due to conflicting meter reading differences, the conversion factor of 1.087 was used to revise the corresponding daily raw water pumped values as well (see table tab "HC Data - Malaba-Tororo (ed.)", columns E, F, cells coloured in blue in the author's Excel file).

Besides this, the record book contained daily values for ACH dose rate (mg/L), as determined by NWSC staff. These values were included in the author's Excel file (table tab "HC Data - Malaba-Tororo (orig.)", column J) and used as control values to verify the ACH dose rates calculated by the author (column I). As the "Analysis ACH dose rate - control value (record book 01.12.2018 - 31.01.2020)" at the end of the table tab shows, the control values largely confirmed the author's calculations. 88 % (n = 375) of the calculated daily values met the control values in the record book (rounded to whole numbers). Of 12 % of calculated values that did not meet the control values, 7 % (n = 31) were in a range of a maximum of +/- 2 mg/L higher or lower than the control values, while 4 % (n = 18) showed deviations of more than 2 mg/L. After adjustment of the daily water volumes according to the procedure described above, still 83 % (n = 353) of the calculated ACH dose rates meet the control values indicated in the record book (rounded to whole numbers), while 10 % (n = 44) are in a range of a maximum of +/- 2 mg/L higher or lower than the control values, and 6 % (n = 27) show deviations above 2 mg/L (see "Analysis ACH dose rate - control value (record book 01.12.2018 - 31.01.2020)" at the end of table tab “HC Data - Malaba-Tororo (ed.)”). For any further analyses, the daily ACH dose rates after adjustment of water volumes were used (see table tab “HC Data - Malaba-Tororo (ed.)”, column K in the author’s Excel file).

Monthly values

As described in subsection “Time series diagrams” in Chapter 3.4.2, the available monthly values for parameters (1) to (7) that were calculated based on daily data were combined with data provided by NWSC in monthly resolution, i.e., data from the quarterly and monthly reporting for the Eastern Region (see record categories viii. and ix. in Table 2). This expansion of monthly data was carried out in the table tab “Monthly values - expanded data” in the author’s Excel file. The data series from this table tab were used for any further analyses. In the process of data expansion, certain modifications such as data filtering and assumptions had to be made by the author to address several peculiarities within the Excel files form the quarterly and monthly reporting. These include contradictions and irregularities within each individual Excel file (e.g., values for a specific parameter that were provided in parallel in different table tabs differ from each other), and between the Excel files (e.g., individual values or value patterns are repeated from one month to one or more of the following months).

For the data expansion, monthly values for the parameters (1) to (7), as calculated from the daily data series (see table tab “HC Summary - Monthly values”), were copied to the table tab “Monthly values - expanded data” in the author’s Excel file. Here, either sum or mean values were included, depending on the respective parameter. For example, raw water quality parameters were included as monthly mean values, while water volumes and chemical uses were included as monthly sum values. Also, the additional parameters coagulant dose rate, coagulant to turbidity ratio, and chlorine (HTH) dose rate were included as monthly mean values in the table tab. This procedure was carried out for each case study DWTP, respectively.

Then, available monthly sum and mean values from the quarterly and monthly reporting for the Eastern Region (see Table 2, record categories viii and ix) were added to the table tab for each parameter, respectively. The headers of the columns including quantitative data provided in digital form are coloured in pink. For most parameters, two or more monthly values were included in different table tabs in the NWSC Excel files that were partially contradicting each other. Furthermore, one or both monthly values from the NWSC Excel files were contradicting with the sum and mean values calculated by the author based on the daily data. Therefore, a selection of monthly values had to be made to create monthly data series for the different parameters. For this, all individual data series were analysed and the available values per parameter and month were compared with each other. To receive monthly data series that were used for further analyses, the following steps were carried out in the indicated order:

1. In case reliable monthly sum or mean values could be calculated based on a sufficiently high number of individual daily values from the hard copy data, these were considered with priority for the respective month. The definition of what was considered as "sufficiently high" was made individually for each case, as explained in comments in table tab "Monthly values - expanded data" in the author's Excel file.

2. For months in which no monthly value could be calculated from the daily data, or in case the respective monthly value was disputable (e.g., due to a low number of available daily input values, due to unreliable daily input values, or due to contradictions between the author's calculations and notes on the data sheets), the monthly values from the quarterly or monthly reporting were considered. The selection of one of the monthly values went as follows:

    a. In case the monthly values for one or more parameter(s) include repeating patterns (e.g., one or more parameter(s) showed the exact same value(s) in one or more month(s) before), all affected values were excluded for the selection. These values were assumed to be transfer errors caused by digital copying of individual values, or of the whole Excel template. The only exception from this was made for (7) chlorine (HTH) use since this parameter is intentionally kept constant during operation at the case study DWTPs, which naturally generates repeating monthly sum values.

    b. If the procedure of excluding repeating values described in (a) resulted in only one definite value remaining for any specific month, this value was selected for the respective month. If the procedure resulted in no value remaining, no value was used for the respective month.

    c. If the procedure of excluding repeating values described in (a) left two or more values remaining for any specific month, one of them was selected that was assumed to best represent reality. The selection was made based on an assessment of the respective value and considering the temporal course of the previous and subsequent monthly values. This procedure was subject to uncertainty, since in many cases, more than one monthly value appeared equally realistic and hence acceptable for the selection. For every individual case, the selection made was explained in a comment in the table tab “Monthly values - expanded data” in the author’s Excel file.

Appendix C: Expert interview with Moses Butele

Interview with Moses Butele (Senior Quality Control Officer in charge of the Eastern Region, NWSC), conducted from 26th May to 2nd June 2020 via telephone calls, emails, and messaging services. **Questions** by David Mondorf and Dr. Mathew Herrnegger. Compiled and edited on 5th June 2020 by David Mondorf.

<u>General questions</u>:

1. **In your opinion, what are the main challenges for drinking water supply in the river basin?**

General challenge:

- Deteriorating raw water quality due to human activity (e.g., farming, agriculture)

Seasonal challenges:

- Dry season: River supplies run dry; Water supply competes with agricultural use: when not enough water is available in the source areas, people divert water to their fields and not enough water is left for the water supply

- Rainy season: Landslides and flooding, mainly in the source areas; pipes get washed away and cannot bring water to the treatment plant

2. **Are there specific challenges during dry season, and specific challenges during rainy season?**

Dry season: Water volumes available for abstraction are reduced, competition with agricultural use

Rainy season: Landslides; flooding of the source areas; Sono water supply scheme: earth movements, earthquakes, landslides, movement of treatment plant pipes (often the reason for missing data for Sono plant during these periods)

3. **Do you see impacts of climate change on the drinking water supply in the river basin?**

Yes.

- Flooding

- Increased rainfalls (e.g., in 2017, it did not rain as much as in 2019 – this information needs verification)

- Patterns of dry seasons and rainy seasons have changed in the last 2-3 years. When rain was expected, it did not rain, and vice versa. People engaged in agriculture often cleared their fields or applied seeds, but eventually, the rain did not come.

4. **How do you evaluate the influence of agricultural land use on drinking water supply in the river basin?**

There is a direct link between agriculture and drinking water supply.

Agricultural land use causes the removal of natural vegetation along the riparian routes of the rivers, which usually acts as a natural filter for water and reduces flash flooding.

When this vegetation is removed in order to plant food crops that are not as good in filtering water, the quality of surface water deteriorates, especially in rainy seasons. More soil is transported to the rivers, which eventually fills up the treatment units.

This has multiple effects on water supply:

- A clogging effect in the treatment units, especially for the filters, leading to the requirement of frequent backwashing and draining of sedimentation tanks regularly (e.g., in dry season, draining must be done roughly once every 3 months, while in rainy season, the same unit has to be drained monthly). Both comes along with high water losses.

- Increased chemical use, especially of coagulant (Aluminium sulphate) and disinfection agents (Chlorine).

<u>Questions on raw water quality</u>:

1. **How are the monthly values for raw water quality measured (overall procedure including sampling, testing, in which laboratory, reporting)?**

NWSC tried to ensure that there is always a person responsible for water quality measurements at the treatment plants. But until recently, at particular treatment plants, no staff was attached.

This used to be the case for Lirima and Sono supply schemes, where no staff to measure water quality was attached until middle of 2018. By that time, Mr. John Ogire went to the plants once per months, collected water samples (one-off grab samples), and brought them to the NWSC regional lab in Mbale for analysis. The analysis results of these single samples represented raw water quality for the whole month for the water supply schemes.

From middle of 2018 on, staff responsible for water quality measurements was attached to the treatment plants. The staff picks and analyses daily raw water samples. From these single analysis results, an average value is created at the end of the month and send to NWSC regional lab in Mbale.

Furthermore, one sample per month shall be collected and brought to the NWSC central lab in Mbale for verification. Under some circumstances, this is not possible. In these cases, Mbale must rely on results that were made on-site.

Procedure for sampling: Grab sampling from the treatment plant inflow (not from the streams).

Analysis: If testing machines and equipment is available at the treatment plants, monthly average values are created.

Some of the labs at the treatment plants are not equipped well enough to do the tests, so some parameters cannot be measured on-site. For these parameters, samples are usually brought to NWSC central lab in Mbale 1x per month. For some months and parameters, this approach was not possible (reason for “ND” values in the Excel files).

From the Excel files, it is unfortunately not clear when a specific value is a monthly average value (based on results from the treatment plant itself), or it is a single analysis result (from NWSC central lab in Mbale).

Reporting: Each treatment plant has a physical record book in its laboratory. The attached staff grabs the samples, does the tests/analyses, and records the value by hand in that record book. Afterwards, the handwritten values are transferred to Excel sheets. At the end of the month, an average value is calculated and send to NWSC regional lab in Mbale.

Besides these daily and monthly analyses, Kampala level is involved once every three months (quarterly reporting sample). For this, Moses Butele himself collects water samples at all supply schemes in the Eastern region and sends them to the central laboratory in Kampala, which does independent analyses of raw water, final treated water, and network and reservoir water samples.

2. **What is done with the obtained values for raw water quality? Do they influence e.g., plant operation, purchasing of chemicals, source water protection, etc.?**

Kampala level receives the monthly reporting values for all water treatment plants (from Northern, Central, Eastern, Western region and from Kampala), and analyses the quarterly reporting samples from all regions in their central lab (*see answer to question 1*).

Based on these analysis results, Kampala level creates a separate report to the head of water quality. In this evaluation step, Moses is not involved. The final report stays in Kampala and is used for decision-making.

Sometimes, there is feedback and questions from Kampala level. If necessary, corrective actions are carried out in the treatment plants based on the feedback.

Example: In case of intensive rainfall and a related increase of observed raw water turbidity, this can be the basis for sending materials from Kampala to the area ahead of time, e.g., coagulant chemicals or new sands for the sand filters = planning of future operations.

Besides this, of course also individual requests from the plants for more material are possible, e.g., for coagulant chemicals.

See also Monitoring & Evaluation, question 1 (below).

3. **In your opinion, do you see other parameters than in the quarterly reporting (e.g., nitrate NO_3^-, pesticides, heavy metals) as challenges or problems for the water treatment?**

Yes, especially pesticides and heavy metals. But in general, these constituents are no serious issue. The treatment systems are good enough to remove any such substance of concern.

While such parameters are not tested at the treatment plants or the NWSC regional lab in Mbale, the quarterly reporting samples (samples that are taken by Moses Butele himself and send to Kampala) are analysed with regards to heavy metals and pesticides.

Most of the results are kept at Kampala and are not shared with Moses Butele. Only in case the analysis results are of concern, Moses Butele is contacted.

For Malaba-Tororo water supply scheme, pesticide problems were discussed in the past.

4. **Is NWSC engaged in source water protection in the river basin?**

Yes, NWSC is carries out source water protection in form of planting of vegetation in the river basin, e.g., trees, wetland vegetation. This intends to help filtering the water and protect the riverbanks. The measures are mainly performed upstream within the river basin.

In the future, these source water protection measures could be enhanced. This would require stakeholder engagement from all stakeholders (farmers, NWSC, environment management agency, local leaders, international donors, others).

5. **Did you observe any changes in raw water quality at the intakes over the years? If yes, which changes and where did you mainly observe them?**

For Lirima and Sono water supply schemes: No, raw water quality basically remained stable. Here, the observed changes are more in terms of seasons: In the dry season, there are no major challenges, while the rainy season is challenging (*see answer to general question 1*).

For Malaba-Tororo water supply scheme: Yes, raw water quality changes occurred in the course of the years. In rainy seasons: Increasingly high levels of the river, very visible also in terms of treatment plant operations.

<u>Questions on operating parameters</u>:

1. **What is done with the monthly values for chemical consumption? Do they influence e.g., plant operation, purchasing of chemicals, source water protection, etc.?**

- Help in planning and procurement of chemicals
- Help in modifying plant designs, e.g., in case chemical consumption is on the increase, manual chemical dosers may be replaced with more efficient motorised (pump) dosers, to reduce on chemical wastage
- Act as a guide to make the decision on intensifying source water protection

2. **Why are some water supply schemes using ACH (aluminium chlorohydrate) as coagulant, while others use alum (aluminium sulphate) for coagulation?**

- Some water treatment plants with very poor raw water quality prefer to use ACH because it appears to be a more effective coagulant and it does not change the pH of the water much, hence final water is not too acidic with ACH. Alum tends to make water more acidic if overdosed, thereby creating the need for Soda Ash (Sodium Carbonate) to correct the pH, which may in the long run increase the cost of treatment.

- Plants with high production (high throughput) also tend to use ACH because based on jar tests, ACH optimum doses are normally lower than alum optimum doses. In other words, ACH appears to be a more potent chemical. Therefore, high production plants use them so dosing pumps are not overworked.

- ACH is also easier to handle, it does not require mixing with water (dilution). Alum requires mixing with water and there is too much dust which if inhaled may cause lung problems.

3. **What does the import of the chemicals look like? What are the specific prices for the coagulants (ACH, alum) and are these prices stable or change over time?**

Unit prices for chemicals used (these prices are not stable; it changes based on time and exchange rate):

- HTH (chlorine) – 6,324 UGX/Kg (1.7 $/Kg)
- Alum – 1,390 UGX/Kg (0.3 $/Kg)
- ACH – 6,671 UGX/Kg (1.8 $/Kg)
- Sodium Chloride – 1,189 UGX/Kg (0.3 $/Kg)

4. **What does the energy infrastructure for the water supply schemes look like? What happens in case of power outages?**

In case of power outages, some plants use generators, others use solar power.

5. **Are values for the monthly energy consumption of the treatment plants available (electricity grid, fuel for generators, solar panels)?**

Yes, monthly energy consumption is available, though not in the quality report I sent, but in a different report compiled by the Plant Engineer.

6. **How can backwashing water volumes for the filters be calculated for each treatment plant?**

Backwashing water volumes are calculated from the backwash meter located on the backwashing tower/tank (records kept by Plant Engineer).

7. **Are values for operationality days of the treatment plants available?**

Yes, operationality days values are available (records kept by plant engineer).

<u>Questions on Monitoring & Evaluation</u>:

1. **After compiling the quarterly reporting datasets, what does NWSC Kampala level further do with the data?**

NWSC Kampala level carries out data analysis and draws trends (e.g., graphs and tables), in order to make decisions.

Example: In case of high energy consumption, should the treatment plant switch to solar energy? Or, in case of high ACH costs, should the treatment plant change to alum?

See also answer raw water quality, question 2.

2. **Is there any long-term evaluation of the operations in the river basin based on the values for raw water quality and/or operating parameters?**

I am not sure if we have this evaluation.

See also answer raw water quality, question 2.

Appendix D: Expert interview with John Ogire

Interview with John Ogire (Senior Water Quality Officer, Tororo Area, NWSC), conducted on 22nd June 2020 via email. **Questions** by David Mondorf.

<u>Questions on on-site water quality analysis in Sono, Lirima and Malaba-Tororo water supply schemes</u>:

1. **Which water quality test equipment is available in the respective on-site laboratories?**

Equipment in the Tororo laboratory:

- Turbidimeter 2020
- pH/Electrical Conductivity meter
- Paqualab (Incubator)
- Floc Tester
- Water still
- Autoclave
- Fridges
- Comparators
- Hot plate
- Burettes and their accessories for titration
- Aspirator and wash bottles
- Turbidimeter tubes

Equipment in Sono laboratory:

- Floc Tester
- Photometer

- Microbiology kit
- pH comparator
- Burettes and their accessories
- Turbidimeter tube

Equipment in Lirima laboratory:

- Floc tester
- Photometer
- Microbiology kit
- pH Comparator
- Turbidimeter tube

2. **Do all three water supply schemes have on-site turbidity test kits available?**

All the three water supply schemes have on site turbidity test kits available.

3. **Until when did you collect water samples on-site yourself (1x/month), and from which point in time was staff attached to the three treatment plants (resulting in daily water quality analyses)?**

For purpose of process control, samples are picked from all stages of water treatment. The type of treatment is convectional for all the water supply systems: abstraction, clarification, filtration, and disinfection.

The samples are picked on sampling schedule on weekly basis for the distribution network and it is done in the zones of East, West, South and North as of Tororo.

For the case of Lirima and Sono schemes, samples are picked twice a month on a strip type of flow since they are operating in gravity flow scheme and there is no properly set up urban setting. The town councils are coming in as new developments. Hence, the supply is much of rural setting.

Questions on raw water quality:

1. **Did you observe any long-term changes in raw water quality at the treatment plant intakes over the years? If yes, which changes and where did you mainly observe them?**

There are long time observable changes in raw water quality.

- Noticeable siltation in the water due to agricultural activities upstream.
- Changing water levels at the rivers of Malaba, Lirima and Lwakhakha.
- Colour and turbidity: These two are proportional to each other. During the rainy season, they are extremely high (colour up to 30,000 PtCo and turbidity up to 2,800 NTU).

2. **Were there discussions on pesticide problems at Malaba-Tororo water supply in the past? If yes, what was the issue?**

No pesticide discussions held on Tororo Malaba water supply.

Questions on additional information and data:

1. **Can you provide an overview of which water supply scheme (Sono, Lirima, Malaba-Tororo) was not operational in which time period? For example, Sono was offline a lot in 2017-2019. In which months?**

All the three water supply systems have peculiar failures.

Sono waterworks:

- Experiences land movements that affect the transmission lines May 2019
- Fence broken down and pipes washed away by storm water from the hills
- Accumulation of silt at the intake

Lirima waterworks:

- Accumulation of silt at the intake

Tororo-Malaba waterworks:

- Electro-mechanical failure of pumps
- Hydroelectric power failures
- Silt accumulation at the intake (mainly during rainy season)

2. **Does a report on energy consumption for the treatment plants exist? If yes, can you share it?**

Energy consumption records are in place.

3. **Does data on filter backwashing water volumes for the three treatment plants exist? If yes, can you share it?**

The Backwash water volumes are in place (find data attached).

4. **Can you share data on operationality days / non-functionality days for the treatment plants?**

The treatment plants are operational for 24 hours.

5. **Can you describe the patterns of dry and rainy season for the years 2017, 2018 and 2019 for the region? Can you recall the respective months?**

The months March to part of June are rainy. Part of June is dry to part of July is dry. Then part of July to early November is rainy. Part November to February is dry spell. Therefore, we experience two dry spells in a year. Hence, we have two seasons for agricultural activities: March to June and July to November.

Appendix E: Photo documentation of study area and case study DWTPs

The following photos were taken by the author and photographer Elias Okemer (where indicated) during the research stay in the study area from 25th January to 8th February 2020. The site visits to the case study DWTPs were performed on 3rd February (Lirima and Sono), as well as on 29th January and 4th February (Malaba-Tororo). Photos from the study area were taken on these days as well. Further photos were provided by NWSC staff member Arima Zubair Isa (where indicated).

Impressions from the study area

i) Landscape in the upper, mountainous part of the SMMRB. Agricultural activity (plantations, livestock) is visible. In case of intensive rainfalls, the topography causes eroded material to be transported with the runoff into river Lwakhakha located in the valley. Photo from the Kenyan side of the SMMRB, taken by Elias Okemer close to the raw water intake of Sono Gravity Flow Scheme (see pictures xlii and xliii).

ii) Landscape in the upper, mountainous part of the SMMRB. The topography creates significant elevation differences and steep slopes. Agricultural activity in the form of terrace cultivation can be observed on the slopes, and grazing livestock in the flatter part. Photo taken by Elias Okemer close to the raw water intake of Sono Gravity Flow Scheme (see pictures xlii and xliii).

iii) Steep, vegetated landscape in the upper part of the SMMRB, in the vicinity of Mount Elgon national park. Photo taken by Elias Okemer close to the raw water intake of Lirima Gravity Flow Scheme (see pictures xix and xx).

iv) Landscape in the upper part of the SMMRB, in the vicinity of Mount Elgon national park. Farming activities can be observed on the steep slopes.

v) River Lirima. The stream water is subject to high flow velocities and turbulence, and appears muddy, silty, and turbid. Bank erosion can be recognised at the riverbanks; in-stream erosion is likely. Rupture surfaces from landslide events are visible in the background, resulting from intensive rainfalls in combination with the steep slopes in the area.

vi) River Lirima and its surrounding vegetation, e.g., matoke plants typical for the region. Photo by Elias Okemer.

vii) Farming activities in the lower reaches of the SMMRB, in Tororo district close to river Malaba.

viii) Grazing cattle in the lower reaches of the SMMRB, in Tororo district close to river Malaba.

ix) Agricultural activity in a natural wetland close to the DWTP of Malaba-Tororo. The plantation in the foreground is for maize, while matoke plants are visible in the background. According to the local farmers, no external fertilisers are applied.

x) Agricultural activity close to the DWTP of Malaba-Tororo. Backwash wastewater from the DWTP is released into this natural wetland. The water from the wetland drains southwards in the direction of river Malaba. Hence, the raw water intake of Malaba-Tororo is not affected by the backwash water.

xi) Maize plantation in the vicinity of the DWTP of Malaba-Tororo. Farming activities take place close to or even in the water. Absence of protective riparian strips to prevent the inflow of sediments into the surface water body.

xii) High water level of river Malaba in the lower part of the SMMRB. Due to intensive rainfalls and the resulting excess of stream water, the contours of the riverbed are not visible anymore.

xiii) A flood area emerges slightly further downstream, where the land is normally used for farming and grazing of cattle.

xiv) Farmers continue their work despite flooding of fields. Photo taken in the lower reaches of river Malaba.

xv) Soil movements regularly affect NWSC infrastructure in the SMMRB. Photo by Arima Zubair Isa.

xvi) Intensive rainfalls in combination with steep slopes frequently result in landslides in the SMMRB. Thereby, large rupture surfaces are created. Often, NWSC infrastructure is affected by these natural hazards. Photo by Arima Zubair Isa.

xvii) Rupture surface after a landslide event. The landslide occurred close to treatment plant buildings of NWSC. Photo by Arima Zubair Isa.

xviii) Landslides and soil movements may dislocate distribution pipes, thereby interrupting the regular operations of NWSC in the river basin. Photo by Arima Zubair Isa.

Lirima Gravity Flow Scheme

A schematic flow diagram of Lirima is shown in Figure 10.

xix) Raw water intake of Lirima Gravity Flow Scheme, located in the course of river Lirima. The area is fenced off to protect the surrounding natural vegetation from human activities. This reduces the inflow of sediments into the intake structure. Exact location: 0°54'08.6"N 34°25'04.5"E. Photo by Elias Okemer.

xx) The intake structure includes a weir for constant level heights, and valves to steer the inflow of raw water to the DWTP. The water flows to the plant by gravity, no raw water pumps are required. Photo by Elias Okemer.

xxi) Signpost of the Lirima Gravity Water Treatment Plant (referred to as "Lirima") in Namisindwa district, eastern Uganda. Exact location of the plant: 0°53'16.3"N 34°24'43.7"E. Photo by Elias Okemer.

xxii) Raw water meter to assess the water quantities flowing into the plant. The corresponding plant records were evaluated as part of the present thesis.

xxiii) In the alum tank, a coagulant solution is prepared by mixing aluminium sulphate ("alum") with water. The coagulant solution is then dosed to the inflowing, turbulent raw water stream.

xxiv) A gravity-operated dosing device doses the coagulant solution from the alum tank to the raw water. Photo by Elias Okemer.

xxv) After dosing of the coagulant, the water flows into flocculation weirs. The hydraulic flocculation system ensures the required mixing and turbulence, as well as sufficient flocculation time. Photo by Elias Okemer.

xxvi) After flocculation, the sedimentation is carried out in one of three clarifiers. Photo by Elias Okemer.

xxvii) After sedimentation, the water is filtered in a rapid sand filtration system.

xxviii) To backwash the filters, the plant has an elevated backwash water tank. Finished water is withdrawn from the clear water well and pumped by backwash pumps to the elevated tank. During backwashing, water flows by gravity from the backwash water tank to the sand filters. Photo by Elias Okemer.

xxix) Control valve for backwash water and service water meter. Photo by Elias Okemer.

xxx) In the chlorine tank, the disinfectant solution is prepared and stored before it is dosed to the water stream. Photo by Elias Okemer.

xxxi) Chlorine solution in the chlorine tank. The chlorine species applied is high test hypochlorite (HTH). Photo by Elias Okemer.

xxxii) Final water tank with water level meters. Photo by Elias Okemer.

xxxiii) Interior view of the pump house. Two backwash pumps are visible in the middle of the photo, connected to green pipes. The electricity required to operate the DWTP of Lirima is provided by a solar panel (see picture xxxv), for which the corresponding solar batteries are visible on the left. A backup petrol generator is visible on the right. Photo by Elias Okemer.

xxxiv) Interior view of the pump house. Inverter by the manufacturer Victron energy on the right. Photo by Elias Okemer.

xxxv) Solar panel providing electricity for the operation of Lirima. Photo by Elias Okemer.

xxxvi) Laboratory at the DWTP of Lirima. Different water quality analyses for raw, clarified, filtered, and final water samples are performed, including for the parameters turbidity, hardness, alkalinity, pH, electrical conductivity, residual aluminium, and residual chlorine. Furthermore, jar tests to determine optimum coagulant doses, as well as chlorine demand tests to determine optimum disinfectant doses are carried out. According to John Ogire, the laboratory is equipped with the following devices: floc tester, photometer, microbiology kit, pH comparator, and turbidimeter tube. Photo by Elias Okemer.

xxxvii) Laboratory equipment. From left to right: Lovibond T3 300 IR turbidimeter; Hach Sension+ MM 374 GLP 2 channel laboratory kit for pH, electrical conductivity, and others; jar testing device. Photo by Elias Okemer.

xxxviii) Treatment chemical store. Photo by Elias Okemer.

xxxix) Stored coagulant chemical (aluminium sulphate), imported from Kenya. Photos by Elias Okemer.

xl) Drying beds for the treatment of wastewater generated during drinking water production, mainly from backwashing and cleaning of clarifiers. Photo by Elias Okemer.

xli) Sand bay for storing of filter sand. Photo by Elias Okemer.

Sono Gravity Flow Scheme

A schematic flow diagram of Sono is shown in Figure 11.

xlii) Raw water intake of Sono Gravity Flow Scheme, located in the course of river Lwakhakha. In the area, the stream constitutes the national border of Uganda (left side of the picture, in western direction) and Kenya (right side of the picture, in eastern direction). Exact location: 0°51'32.6"N 34°26'40.6"E. Photo by Elias Okemer.

xliii) Intake structure of Sono Gravity Flow Scheme. The intake of the new DWTP which is in operation today is visible in the middle of the picture. On the left is the former intake structure of the old plant which is no longer used today.

xliv) Signpost of the Sono Gravity Water Treatment Plant (referred to as “Sono”) in Namisindwa district, eastern Uganda. Exact location of the plant: 0°51'22.9"N 34°26'36.0"E.

xlv) Overview of the DWTP of Sono. Sedimentation stage (clarifiers 1 and 2) in the centre of the picture, behind it the chlorine tank for disinfectant dosing located under the roof. On the right is the clear water well for the final water. Photo by Elias Okemer.

xlvi) Opposite point of view to the previous picture. The chlorine tank for disinfectant dosing is located under the roof, behind it the clarifiers for sedimentation. Elevated backwash water tank on the right. The blue barrel on the right is the alum drum facilitating coagulant dosing to the raw water. In the background is the plant building including the office, laboratory, storage spaces, etc. In the lower part is the clear water well for the final water. Photo by Elias Okemer.

xlvii) Alum mixing drum and coagulant dosing device. In the alum drum, a sack containing alum is brought into contact with water. The alum solution flows out from the tank through a tube and is dosed to the raw water by the dosing device.

xlviii) A gravity-operated dosing device doses the coagulant solution from the alum drum to the raw water.

xlix) After dosing of the coagulant, the water flows into these flocculation chambers. The treatment stage is designed considerably smaller compared to the hydraulic flocculation system at Lirima. According to the plant overseers, it does not provide sufficient time for the coagulant chemical to mix and react with the water. Therefore, flocculation cannot take place properly. After the flocculation chambers, the water enters the clarifiers. Photo by Elias Okemer.

l) Both clarifiers were not in operation at the time of the site visit. Photo by Elias Okemer.

ll) As the filtration stage was not in operation as well at the time of the site visit, the raw water from the clarifiers was taken up by these tubes, bypassing the filter, and transferred directly to the clear water well.

Iii) Clear water well with water level meters.

Iiii) Chlorine solution in the chlorine tank. The chlorine species applied is high test hypochlorite (HTH). The disinfectant solution is dosed directly to the clear water tank.

liv) Clear water well and distribution pipe, including valves to steer the outflow into the supply network.

lv) Damages at the clear water well of Sono. The area is prone to land movements, resulting in frequent supply interruptions at the DWTP.

lvi) Rapid sand filters. The treatment stage was not in operation at the time of the site visit and instead bypassed by the tubes shown in picture liv. Photo by Elias Okemer.

lvii) Elevated backwash water tank. Like at Lirima, final water is withdrawn from the clear water well and pumped by backwash pumps to the elevated tank. During backwashing, water flows by gravity from the backwash water tank to the sand filters. Since the filters were not in operation at the time of the site visit, the backwashing system was not used as well. Photo by Elias Okemer.

lviii) Solar panel providing electricity for the operation of Sono. Photo by Elias Okemer.

lix) Laboratory at the DWTP of Sono. Different water quality analyses for raw, clarified, filtered, and final water samples are performed, including for the parameters turbidity, colour, hardness, alkalinity, pH, residual aluminium, total residual chlorine, and free residual chlorine. Furthermore, jar tests to determine optimum coagulant doses, as well as chlorine demand tests to determine optimum disinfectant doses are carried out. According to John Ogire, the laboratory is equipped with the following devices: floc tester, photometer, microbiology kit, pH comparator, burettes and their accessories, and turbidimeter tube. Photo by Elias Okemer.

lx) Drying beds for the treatment of wastewater generated during drinking water production, mainly from backwashing and cleaning of clarifiers. The drying beds were not in operation at the time of the site visit.

Malaba-Tororo Water Supply

A schematic flow diagram of Malaba-Tororo is shown in Figure 12.

lxi) Signpost of the raw water pumping station of Malaba-Tororo Water Supply (referred to as "Malaba-Tororo") in Tororo district, eastern Uganda. Exact location: 0°37'31.7"N 34°12'24.8"E. Photo by Elias Okemer.

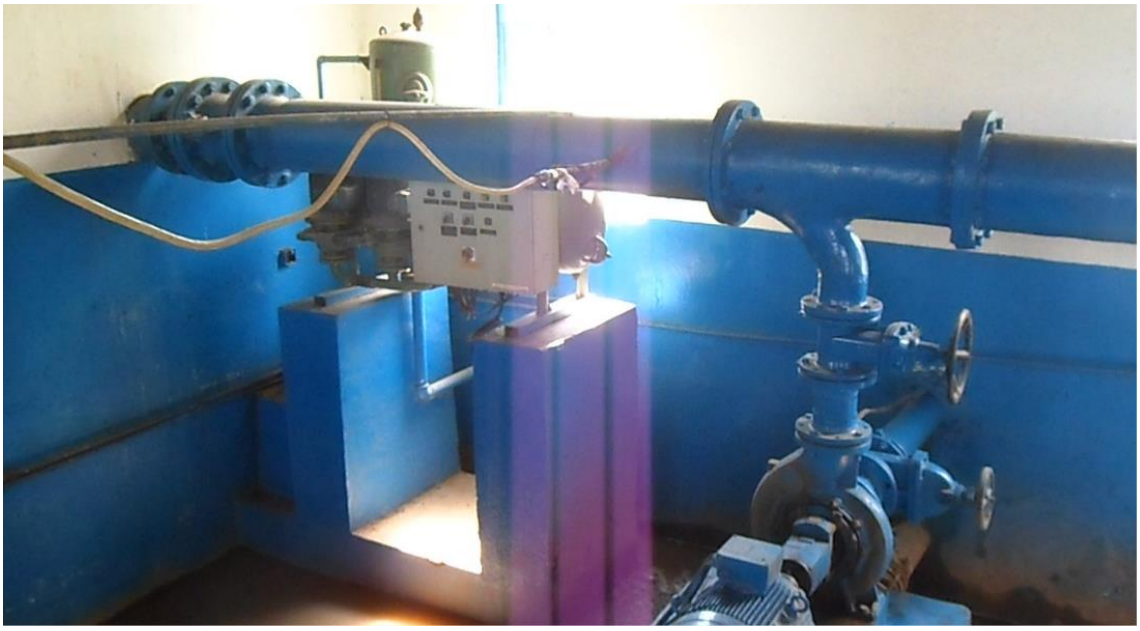
lxii) Raw water intake of Malaba-Tororo, located in the lower reaches of river Malaba. In the area, the stream constitutes the national border of Uganda and Kenya. The stream water appears muddy, silty, and turbid.

lxiii) Raw water intake pumps of Malaba-Tororo. Three pipes are visible on the water surface, another pump is located under water. When the intake pipes get too clogged due to sediment deposits, the corresponding pumps are shut off to allow for the sediment to be flushed away by the turbulent stream water. After a while, the pumps can be turned on again and operation can continue. Furthermore, a diver removes sediments regularly.

lxiv) Pump house for raw water pumps, coagulant dosing, and coagulant storage at Malaba-Tororo. Photo by Elias Okemer.

lxv) The raw water pumps draw water from river Malaba in and transport it to the DWTP. Two pumps are in operation, two in standby. Photo by Elias Okemer.

lxvi) Dosing device to apply the coagulant Aluminium Chlorohydrate (ACH) from the blue barrel to the raw water. The dosing device is operated by electrical dosing pumps. One pump is in operation, two are in standby. Photo by Elias Okemer.



lxvii) The dosing device applies the coagulant chemical through a hose into the raw water pipe. Due to turbulence in the pipe, the coagulant is rapidly mixed with the raw water. Simultaneously, the water stream is transported to the DWTP.

lxviii) Storage room for ACH in the pump house. About two barrels per day were used in average at the time of the site visit, at a stock of about 130 barrels. Photo by Elias Okemer.

lxix) The coagulant chemical (ACH) has the type designation “ZetaFloc 2300” and is imported from South Africa from the manufacturer Protea chemicals. The coagulant solution in the barrels is ready for application to the raw water stream and requires no further preparation.

lxx) Signpost of the DWTP of Malaba-Tororo. Exact location of the plant: 0°37'47.5"N 34°12'18.8"E. The DWTP consists of two treatment lines operated in parallel, one old and one new line. All following pictures are from the new line, unless noted otherwise.

lxxi) Sedimentation basin. Two clarifiers are operated in parallel at the new line. Photo by Elias Okemer.

lxxii) After flocculation that took place in the raw water pipe, dense flocs can be observed in the front part of the clarifier. The flocs settle quickly, resulting in less turbid water in the rear part of the clarifier. The clarifiers need to be cleaned from sediments approximately every three months. Photo by Elias Okemer.

lxxiii) Sand filters at the new line. The filter media was exchanged at the time of the site visit. Photo by Elias Okemer.

lxxiv) Overview of the maintenance works at the sand filters. Photo by Elias Okemer.

lxxv) Rapid sand filtration at the old line of the DWTP. Photo by Elias Okemer.

lxxvi) Operations building for the chlorine dosing and backwashing systems. Photo by Elias Okemer.

lxxvii) Interior view of the backwashing station. Two electrical pumps transfer water from the clear water wells to the backwashing tanks. One pump is in operation, one in standby. Photo by Elias Okemer.

lxxviii) Air backwash blowers to provide air to the filters during backwashing. Photo by Elias Okemer.

lxxix) Service water meter and control valves for the backwash water. The junction allows to feed the elevated backwash water tanks from both the new and old line with final water from the clear water well.

lxxx) Elevated backwashing water tank of the new line. In backwashing mode, water flows by gravity from the elevated tanks to the sand filters. Simultaneously, air is supplied by the air backwash blowers. Photo by Elias Okemer.

lxxxi) Chlorine tank and dosing device in the chlorine room. Photo by Elias Okemer.

lxxxii) Top view of the chlorine tank in which the disinfectant solution is prepared and stored before it is dosed to the water stream. The chlorine species applied is high test hypochlorite (HTH).

lxxxiii) The dosing device applies the disinfectant solution through the floor of the chlorine room to the water stream that enters the final water tank after filtration.

lxxxiv) Final water tank with water level meters.

lxxxv) Interior view of the final water tank. Photo by Elias Okemer.

lxxxvi) Five electrical pumps transfer water from the two final water tanks (one each for the old and new line) to the reserve tank on Tororo hill. From there, the water is distributed by gravity to the water users. Two to three pumps are in operation, two to three in standby, depending on the operational conditions. Photo by Elias Okemer.

lxxxvii) Surge vessels to maintain correct pressure in the distribution network. Photo by Elias Okemer.

lxxxviii) The electricity required to operate the DWTP of Malaba-Tororo is provided by electricity from the grid, as well as a backup diesel generator. For the former, the photo shows the transformers, and the electricity grid in the background of the picture. Photo by Elias Okemer.