Water Management Through Rainwater Harvesting, Flood Mitigation, and Greywater Reuse

A case study at a school in rural Tanzania

Master's thesis in Infrastructure and Environmental Engineering

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Photo showing the school building at the case study site. Photo taken 2025-03-12 by the authors of the report.
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Abstract

Access to safe and reliable water remains a challenge in many rural areas in Tanzania, where the seasonal variations lead to problems with both water scarcity and flood risks. One site facing water management challenges is Tumaini Open School, located in a rural area in Tabora, Tanzania. This study investigates the potential of improving water management at the school through rainwater harvesting (RWH), flood mitigation, and greywater reuse. Fieldwork including collection of GPS data, water sampling, soil infiltration testing, and general site observations was conducted during a ten week visit to the site. The GPS data ant the measured soil infiltration was used in flood simulations performed in Scalgo Live, while the water samples were analysed for pH, turbidity, and conductivity.

The results showed that harvesting rainwater from the roofs of the school building and storing it in a 60 000 L tank could cover a substantial part of the water demanded for irrigation and construction purposes. To ease the problem with soil erosion on the roads due to heavy rainfall, simulations proved constructing swales alongside these roads was an efficient mitigation measure. For greywater management, two low-cost filtration methods, layered filtration barrels and elevated plant filtration beds, are suggested for on-site treatment of greywater to enable greywater reuse for non-potable purposes at the site. Although the suggested interventions were not implemented on the site in this study, the findings still provide valuable insights into feasible and locally adapted water management strategies. The proposed solutions can be used to enhance water sustainability at Tumaini Open School and offer guidance on how to address water-related challenges in other rural communities.

Key words: Flood mitigation, Greywater reuse, Rainwater harvesting (RWH), Rural water supply, Sustainable water management, Tanzania.

Vattenhantering genom regnvattenuppsamling, översvämningsåtgärder och återanvändning av gråvatten

En fallstudie vid en skola i ett landsbygdsområde i Tanzania

Examensarbete inom masterprogrammet Infrastruktur och miljöteknik

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Sammanfattning

Tillgång till säkert och tillförlitligt vatten är en utmaning i många landsbygdsområden i Tanzania, där säsongsvariationer leder till både vattenbrist och ökad risk för översvämningar. Tumaini Open School ligger i ett landsbygdsområde i Tabora, Tanzania och upplever utmaningar kring vattenhantering relaterat till dessa problem. Denna studie undersöker möjligheterna till att förbättra vattenhanteringen på skolan med hjälp av regnvatteninsamling, översvämningsåtgärder och återanvändning av gråvatten. Under en tio veckors lång fältstudie på platsen så utfördes fältarbete bestående av insamling av GPS-data, vattenprovtagning, infiltrationstest i jord samt generella observationer och mätningar. GPS-datan samt information om jordens infiltration användes för att simulera översvämningar i Scalgo Live medan vattenkvaliteten för vattenproverna analyserades genom att testa pH, turbiditet och konduktivitet.

Resultaten visar på att en stor del av vattenbehovet för bevattning och byggnadsarbeten kan täckas genom att samla in regnvatten från skolbyggnadens tak och förvara det i en 60 000 L stor vattenlagringstank. För att lindra problem med erosion på vägar till följd av kraftigt regn så föreslås svackdiken byggas längs med vägarna, vilket visat sig vara en effektiv lösning i simuleringar. För hanteringen av gråvatten så föreslås två kostnadseffektiva filtreringsmetoder, skiktad filtrering genom tunna och upphöjd växtbädd, för att rena och möjliggöra återanvändning av gråvatten på plats. Trots att de föreslagna åtgärderna inte implementerades på plats i denna studie ger resultaten ändå värdefulla insikter i genomförbara och lokalt anpassade strategier för vattenhantering. Föreslagna åtgärder kan användas för att bidra till en mer hållbar vattenhantering på Tumaini Open School och ge vägledning i hur utmaningar relaterade till vatten kan bemötas på andra ställen med liknande förutsättningar.

Nyckelord: Hållbar vattenhantering, Regnvatteninsamling, Tanzania, Vattenförsörjning på landsbygden, Återanvändning av gråvatten, Översvämningsåtgärder.

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Gothenburg, June 2025

Emma Green Blomroos & Emil Tengmer

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List of Acronyms

CHSRI	Constant Head Single Ring Infiltration
DEM	Digital Elevation Model
DTM	Digital Terrain Model
DRI	Double Ring Infiltration
EWB	Engineers Without Borders
FHSRI	Falling Head Single Ring Infiltration
FNU	Formazin Nephelometric Units
GIS	Geographic Information Systems
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
ITCZ	Intertropical Convergence Zone
IWRM	Integrated Water Resource Management
LiDAR	Light Detection and Ranging
LOS	Line of Sight
Lpd	Litre per Day
Lpcd	Litre per Capita and Day
Lpcw	Litre per Capita and Week
NTU	Nephelometric Turbidity Units
PE	Polyethylene
PP	Polypropylene
RWH	Rainwater Harvesting
SDG	Sustainable Development Goals
SUDS	Sustainable Urban Drainage System
TSS	Total Suspended Solids
UAV	Unmanned Aerial Vehicle

1 Introduction

Water is essential for all forms of life (UNESCO, 2019). It is a fundamental resource for human health, agriculture, industry, and ecosystems (Ferrero et al, 2024). Access to clean and sufficient water is critical not only for survival but also for ensuring sustainable development, public health, and economic stability (World Health Organization [WHO], 2023). Despite its importance, many regions around the world face growing challenges in managing water resources, due to both natural variability and human influence (Mekonnen & Hoekstra, 2016).

The global temperature has been increasing in recent years, and the past ten years are all among the ten warmest years that have been recorded by humans (World Meteorological Organization [WMO], 2025). The global temperature in 2024 was the highest ever observed in the instrumental records, and according to data from six international datasets, it was the first year ever where the global average surface temperature was more than 1.5°C higher than the average temperatures in preindustrial time. This rising temperature is an indicator of climate change, which intensifies the frequency and severity of extreme weather events such as water scarcity and flooding (Frame et al., 2020). Rising temperatures lead to increased evaporation and higher atmospheric moisture levels, which results in more intense and prolonged rainfall in many regions (Tabari, 2020; Trenberth, 2011). The shifts in global water patterns create a paradox where communities may face excessive rainfall and suffer from severe water scarcity within the same year (Dai et al., 2018).

Water scarcity has become one of the most critical environmental and social challenges of the 21st century and it affects billions of people worldwide (Mekonnen & Hoekstra, 2016). Scarcity occurs when water demand exceeds supply, often due to climatic variability, overextraction of groundwater, salinisation from seawater, deforestation, and inefficient water management (Belhassan, 2021). Many regions experience seasonal water shortages where rainfall is concentrated to a few months while dry periods dominate the rest of the year (Shao et al., 2015). Without effective systems to store and manage rainwater, this resource is lost through infiltration or evaporation (UNESCO, 2019; Loucks & Van Beek, 2017).

While water scarcity poses a long-term challenge to water security, floodings also continues to threaten communities across the globe. Floods result from heavy precipitation due to weather events such as hurricanes, thunderstorms, and monsoons (Kundzewicz, 2013), as well as from river overflow and inadequate drainage (Lian et al., 2012). Land use changes, such as deforestation, urbanisation, and agricultural expansion further reduce the land's natural capacity to absorb water (Chang & Franczyk, 2008). Globally, floods disrupt livelihoods, damage infrastructure, and threaten public health by contaminating drinking water (Kundzewicz, 2013; Jonkman, 2005). Between 2013 and 2023, the worldwide economic losses caused by floods amounted to approximately 100 million USD (Statista, 2024). The consequences are especially severe in regions with inadequate infrastructure and limited resources for mitigation and recovery.

Africa is particularly vulnerable to the impacts of both water scarcity and flooding, due to its geographic and socio-economic conditions (Nkomo et al., 2006). Many regions experience highly variable seasonal rainfall patterns (Nicholson, 2017), largely influenced by the Intertropical Convergence Zone (ITCZ), a climate system that brings intense rainfall to some regions while it leaves others in prolonged dry periods (Camberlin, 2018). This seasonal variability makes it difficult for communities to secure a stable water supply and contributes to cycles of drought followed by flooding (Suzuki, 2011). Periods of drought threaten food production, economic stability, and public health (Dai et al., 2018), while floodings can cause damage to sectors such as agriculture, health, education, and water supply (Codjoe & Atiglo, 2020). During floods, croplands are often submerged, infrastructure is damaged, and communities are left vulnerable to disease outbreaks, especially in flood-prone regions without resilient public services (Douglas, 2017; Reed et al., 2022). In many cases, the impacts of floodings are long-lasting and forces vulnerable populations into periods of poverty and underdevelopment. Meanwhile, insufficient infrastructure for drainage and water storage exacerbates both flood impacts and water shortages (Tucci, 2007). The combination of flood-related destruction and water shortages in Africa contributes to both environmental and socio-economic instability across the continent.

1.1 Background

Tanzania, like many African countries, faces significant challenges related to both water scarcity and flooding (Kikwasi & Mbuya, 2019). The country's diverse geography includes flat lowlands, highland plateaus, and extensive river systems, which makes some areas prone to periodic floods (Kangalawe, 2017). However, despite receiving substantial rainfall during the wet seasons, Tanzania also experiences prolonged dry periods every year, especially in the central and northern regions (Borhara et al., 2020). The country's topography leads to significant variation in rainfall across regions during the rainy season (Luhunga, 2025). Some areas receive 534 mm annually, while others receive up to 1837 mm. This study was performed in the Tabora region, which receives an annual total precipitation of around 800 to 1100 mm (Time and Date, n.d.; Weather & Climate, n.d.). However, as the precipitation is concentrated to the months during the rainy season, the monthly precipitation can be more than 200 mm during the wettest months.

Parts of Tanzania experiences two rainy seasons: one with longer rain from March to May, and one with shorter rain from October to December (Luhunga et al., 2016). These seasons are influenced by the ITCZ, which is a low-pressure belt that encircles the Earth near the equator where trade winds converge. The convergence leads to warm, moist air rising and then cools and condenses to form clouds, which results in frequent rainfall (Camberlin, 2018; Suzuki, 2011; Borhara et al., 2020). During March to May, the ITCZ shifts northward and brings prolonged and intense rainfall to most of the country. From October to December, the ITCZ moves southward and result in shorter, less intense rains. Due to the movement of the ITCZ, the country can be divided into bimodal and unimodal regions, depending on whether they experience two or one rainy seasons (Luhunga et al., 2016). Most regions in Tanzania falls within the unimodal zone, including the south, west, and the central regions. Since Tabora, which is the location of the case study, is in the central western part of Tanzania, the region is unimodal and experience one long rainy season. They do however still experience the differences in both longer and shorter rainfall events.

During the wet season, an abundance of rain can lead to several water-related challenges. Floodings in Tanzania have devastating consequences, particularly in low-lying and poorly drained regions (Omambia & Gu, 2010). Infrastructure such as homes, roads, and schools are frequently damaged, which can cut off communities from vital services (Haasnoot et al., 2011). Agricultural lands are frequently submerged, leading to food insecurity and economic losses (Omambia & Gu, 2010). Additionally, stagnant water serves as breeding grounds for mosquitoes, increasing the risk of malaria and other diseases spread by mosquitos (Dai et al., 2018). The interlinked challenges of water scarcity and flood-related destruction highlights the urgent need for integrated and sustainable water management strategies to build resilient communities and ensure long-term access to safe water in Tanzania.

Water scarcity is especially problematic in areas where high evaporation rates and limited groundwater recharge occur (Liwenga, 2008; Zorita & Tilya, 2002). Poor water management practices, such as inadequate maintenance of infrastructure, inefficient irrigation methods, and a lack of investments in storage systems limit the capacity to store and distribute water effectively. Additionally, climate change exacerbates the problems by causing more irregular rainfall patterns, which further strain existing resources by making it more difficult to capture, store, and manage water consistently (Kimaro, 2019). As rainfall becomes more unpredictable (Omambia & Gu, 2010), sustainable water management becomes increasingly important. In rural parts of Tanzania, the lack of reliable access to clean water affects hygiene, sanitation, and public health. This leads to the spread of waterborne diseases such as cholera and typhoid (WHO, 2023). Without infrastructure for capturing and storing seasonal rainwater, communities are left significantly more vulnerable during dry periods.

The case study area, Tumaini Open School, is located in the Tabora region in Tanzania and is an educational institution that provides opportunities for secondary education to students who are unable to attend traditional schools (Tumaini Open School, n.d.). The school plays an important role in the local community by offering inclusive and flexible learning environments, especially for vulnerable individuals. However, like many institutions in the region, Tumaini Open School is affected by the challenges of inconsistent water supply, poor drainage infrastructure, and exposure to flood risks during the rainy season.

1.2 Aim

The aim of this master's thesis is to solve challenges regarding the water management at the case study area Tumaini Open School to ensure a safe environment for the people working and studying at the site. Specifically, the project aims to improve water accessibility by harvesting and storing rainwater for later use, mitigate the flood risks caused by heavy rain during the rainy season, and propose solutions for on-site treatment of greywater to enable greywater reuse. The proposed solutions should be suitable for the local environment with regards to both cultural and social aspects. It is important that the local customs are considered for the solutions to not only be implemented, but also to keep functioning properly once they have been put in practice.

1.2.1 Research questions

The project aims to answer the following research questions:

- What is the optimal design and solution for a rainwater harvesting (RWH) system at the site that account for storage capacity, cost effectiveness, and local rainfall patterns?
- How can sustainable water management strategies be designed to mitigate flood risks at the site?
- What are the most feasible and sustainable methods for on-site greywater treatment and reuse?
- How can locally available materials and expertise be incorporated into the design of solutions to ensure sustainability and cost effectiveness?

1.3 Limitations

The project is limited to the Tumaini Open School in Tabora, Tanzania and the field work is limited to 10 weeks in February to April 2025. The site will therefore only be investigated during the rainy season. Furthermore, the study is limited to the resources and materials available locally and within the project's budget. The methods are therefore adapted and simplified since there was no access to a properly equipped laboratory during the field study. The focus on the water reuse is mainly for irrigation and construction purposes. The study mostly investigates greywater solutions in a theoretical way and therefore, the only sampling and analysis of greywater is made from the laundry water of the authors' own clothes. The effects of floodings are only investigated by observing floodings caused by rain.

2 Case study area

Tumaini Open School is located in a small village called Isukamahela, nearly 15 km south of the city Tabora in Tanzania. In Figure 2.1, the location of the school in relation to both Tanzania and Tabora can be seen. The village is considered rural as it is very low-populated, heavily reliant on farming, has low night light intensity, not many impervious surfaces, and is relatively secluded from the city (Wineman et al., 2020). However, it is still partly connected to the road network leading into Tabora. The school, which began construction in 2020 and later opened in 2021, has been collaborating with Engineers Without Borders (EWB) ever since its opening. Since then, EWB has conducted several projects there to help improve the situation. In one project performed by volunteers, a solar power system was installed (Tumaini Open School, 2024). The school previously had frequent problems with power outages due to an unreliable power grid. Following the installation of a new power system, solar energy has ensured that the school now has power even during power outages. Other projects involved proposing a land use plan for the expansion of the school, or suggestions on how to make the operation of the school more sustainable. The school currently has around 55 students that both study and live at the school, but it is constantly looking to expand to accommodate more students. The long-term goal is to be able to educate up to 450 students at the same time.

Figure 2.1: a) The placement of Tumaini Open School in relation to Tanzania (Google Earth, 2021). b) The placement of Tumaini Open School in relation to Tabora (Google Earth, 2023).

Sustainability is a key point in the organisation at Tumaini Open School. First and foremost, the school supports young women by creating a stigma-free environment where they are allowed to continue their education (Tumaini Open School, n.d.). This is a way to ensure social sustainability as it strengthens the women's rights in the society. The school also strives towards becoming as self-sufficient as possible and it already has a small farming area with animals used for husbandry, as well as trees and plants that grow food. The produce from the farm is currently only used to feed the students and the staff at the school, but once the school expands in the future, their aim is to also sell a portion of it to earn money. Currently, it is only possible for the school to grow crops during the wet season as they lack sufficient access to water during the dry season. The extra money from a business could be well needed since the school relies heavily on private donations or companies to be able to fund their organisation and its expenses.

2.1 Current and future land use

In 2022, representatives from EWB conducted a land use plan for the school to follow when constructing new buildings. Since then, the school has expanded its land area and therefore, the placement of the new construction projects at the site has deviated from the previous plan. A map of the current land use is presented in Figure *2.2* and shows the existing buildings, as well as buildings currently under construction. The figure also shows the locations of the water-related structures, which include plastic tanks filled with water, a septic tank, a shallow well, a potential placement for a future borehole, graves, and a small incinerator.

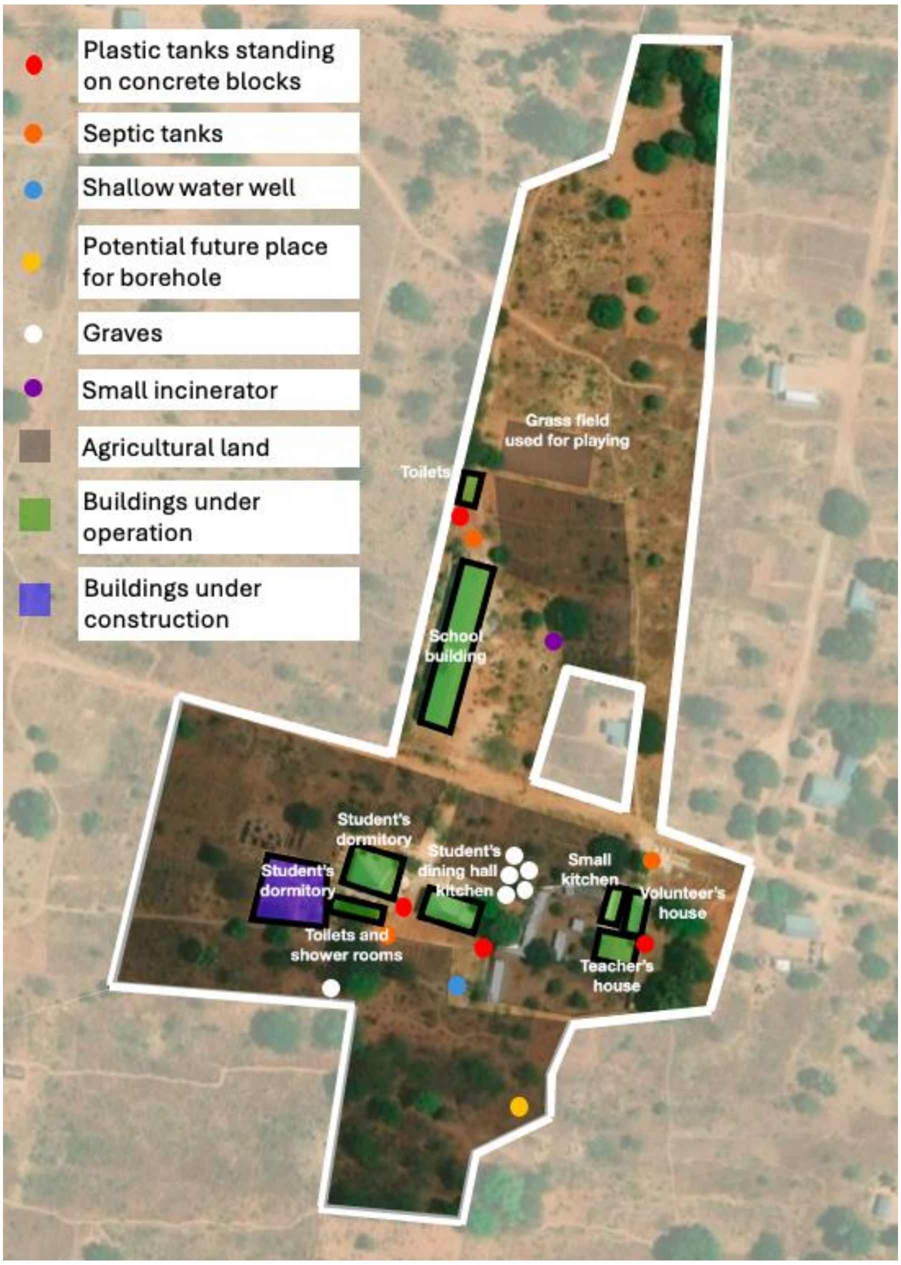

Figure 2.2: Land use of Tumaini open school including existing buildings, buildings under construction, and different water solutions.

Across the land, there is a larger road where vehicles can travel, for example those transporting building materials to the school during construction work. The road also divides the land area into a residential area in the south and an educational area in the north. The educational area so far consists of a school building with four classrooms, one computer room, one teachers' office and one storage room. There are also bathrooms located next to the school which consists of four toilets. The bathrooms next to the students' dormitory consists of four toilets and eight shower rooms, and inside the student dormitory, there is another toilet that can be used at night. The students' dormitory accommodates around 55 people, the house for the volunteers, three persons (currently two volunteers and one teacher), the house for the teachers, three persons, and the small kitchen building next to it houses, another teacher. The farming land for animals by the living area for teachers and volunteers consists of one sheep, nine pigs and around 45 chickens, turkeys, ducks, and other bird species. These animals roam around freely and defecate all over the area, but mostly inside the gates surrounding the volunteers' and teachers' houses. Next to the students' dining hall there are seven graves located, and a bit further south on the land area, there is another one. Most of these graves were already there before the land was purchased, however, at least three of them have been dug since 2022.

Due to the land expansion, there is no updated land use plan available. However, the northern area is planned to remain an educational area while the residential area will remain in the southern part of the land. The ongoing construction of a new dormitory for students next to the existing dormitory is expected to finish in the spring of 2025. The buildings that are next in the priority order of being constructed as of now are all educational: science laboratory, library, and administration office. The living area for teachers and volunteers is planned to expand to be able to host more teachers as more teachers are needed when the number of student increases. To accommodate for more teachers, the animal farm is planned to be either removed or moved to a new place outside of the school area. However, some chickens are still planned to remain in the area.

The foundation of existing buildings at the site are mostly built with concrete blocks and covered with cement, and the roof structures are constructed with wooden beams and then covered by plates of stainless steel. Something that characterises the buildings in the area is that many of them have very steep roofs. This is especially evident on the dormitory and the volunteers' house. The reason for this is partly for aesthetical reasons, but also to avoid standing water on the roofs and hurry the drying process to prevent corrosion from occurring.

2.2 Water supply

The school is connected to the municipal water supply system and receives municipal water in taps installed in bathrooms, kitchens, and open surfaces around the school area. This water is used for hygiene purposes like showering, flushing toilets, household chores such as cleaning, washing clothes and dishes, irrigation, construction work, and for drinking and cooking. There are however issues with the reliability of the municipal water supply system and the school often experiences shutdowns where no water is provided to the school. These shutdowns generally last for a couple of days up to a week. The shutdowns are unpredictable, and no warning is given prior to them. To prepare for the shutdowns, the school has installed four 5 000 L overground plastic tanks standing on concrete blocks in several locations around the school grounds. These tanks are filled with municipal water and are used for storage, but water is also retrieved from them daily. When water shutdowns occur, the filled tanks enable access to water even though no new inflow occurs. This can help prolong the time the school has access to water, but during long-lasting shutdowns it is not enough.

The school also has a shallow well that is utilised to retrieve additional water. The well is around 12 m deep and the water from it is only used for irrigation purposes and construction work. However, the well is also an unreliable water supply source. This is because it does not contain very large volumes of water, and the groundwater supply is often limited. Currently, the school does not harvest any rainwater. This is something that another nearby school and other larger buildings in the area do though, and it is a method that can be used to decrease the reliance on the municipal water supply system. For example, a school located only around 500 m from the Tumaini campus has implemented a RWH solution. There, water is collected from roofs and transported by gutters into a tank where it is stored for later usage. The tank is made of concrete, stored partially underground, and can hold a maximum volume of 46 000 L. This system was implemented in 2007, but due to a lack of maintenance and management, it is no longer in use today. Tumaini Open School has assigned a point at the school as a potential location for a future borehole to retrieve groundwater. The borehole is yet to be constructed, and no required investigations have been made of the site yet.

2.2.1 Installation of a borehole

Drilling a borehole for groundwater extraction is a commonly used approach to access reliable water sources in areas where water supply requires additional supplementation (Kashaigili, 2010). Borehole drilling in Tanzania is usually done by private contractors who are registered with the Ministry of Water. Some factors affecting the costs are depth, geological conditions and location of the site (Kashaigili, 2010). Typical costs in Tanzania ranges from 6 000 to 12 000 USD for a complete system including drilling, casing, testing, and pump installation. This is considered expensive.

In Tanzania, all groundwater extraction activities are regulated by the Water Resources Management Act No. 11 of 2009, which states that any institution or private person intending to drill and use groundwater must apply for two different permits (United Republic of Tanzania, 2009). Groundwater Drilling Permit is required before drilling begins and Groundwater Abstraction Permit is issued after drilling. Applications typically require a hydrogeological survey report, coordinates of the proposed drilling site, estimated abstraction volumes, and the intended use of the water. Unauthorised drilling is illegal and can result in fines or closure of the borehole (United Republic of Tanzania, 2009; Kashaigili, 2010).

Before drilling, it is important to conduct a hydrogeological assessment to determine groundwater availability, depth, and potential sources of contamination (Kashaigili, 2010). The United Republic of Tanzania (2019) recommends that a borehole has a minimum distance of 20 m to septic tanks and greywater discharge areas, 30 m to pit latrines and waste disposal sites, and 50 m from burial sites. As permeable soils or shallow aquifers significantly increase the risk of contamination from nearby sources, the soil permeability can affect the recommended distances (World Bank, 2019).

Therefore, local topography, soil type, groundwater flow direction, and land use history must be assessed before confirming a drill site.

2.3 Water usage

All the toilets installed at the school are water toilets, meaning they are flushed with water after usage. The toilets in the volunteers' house are standard cistern flushing toilets which means that they are connected to a water tank so they can be flushed by pressing a button (Sanihub, n.d.). The rest of the toilets are pour-flush latrines which means that they are flushed by pouring water from a bucket. The pour-flush toilets are generally less water demanding as they require around 1-3 L while a cistern flushing toilet uses around 6-9 L per use if they are modern, and even more if they are old (Sanihub, n.d.). If a person on average flushes a toilet 5 times per day, the estimated amount of water used for toilet flushing at Tumaini Open School is around 10 litres per capita and day (lpcd).

Similarly, the showers in the volunteers' house differ from the other buildings. In the volunteers' house, showers with running water are installed, while the other bathrooms on the school grounds consist of shower rooms where water, again, is poured from buckets. When comparing the water consumption of the two techniques it was found that showering by using a bucket requires less water than using a shower head with running water (George et al., 2024). According to the Environmental Protection Agency [EPA] (2025d) a shower head uses around 9.5 L/min. Showering for 5 minutes would therefore result in a usage of just under 50 L of water. The water consumption of showering with a bucket is less studied but based on own experiences at the case study area, it is estimated to be around 10 L for an equivalent shower. All the water used is cold water as there is no access to warm water.

All the washing of clothes is done by hand by using buckets filled with water and detergent, and a bucket filled with only water when rinsing the clothes. If many clothing items are washed at once, it can be necessary to change the water once or twice for both the washing and the rinsing process. For one person to wash one week's worth of clothes, an estimated amount of 10 L is used for washing, while another 10 L is used for rinsing, making the total water consumption for washing clothes around 20 litres per capita and week (lpcw). This is equivalent to almost 3 lpcd. While the daily average consumption for washing clothes is not very large, the activity demands for rather large volumes of water at once.

The washing of dishes at the site is also done by hand by using a container filled with water to wash everything with soap, and another container filled with water to rinse the dishes. To perform a daily wash of dishes for 5 teachers or volunteers, an estimated amount of 15 L is consumed. This is equivalent to 3 lpcd. The low water consumption is explained by little usage of running water and instead mostly using the same water the whole batch of dishes. The students water consumption for dish washing is assumed to be even lower as they do not use as many utensils when cooking, and no cutlery when eating.

2.4 Water demand

There is no information available about how much water is used for different activities at the school. However, as the school purchases municipal water they have a bill containing information about how much water is purchased every month. This water bill shows how the water usage is distributed over three different areas: educational area, residential area for volunteers and teachers, and residential area for students. The data is measured in cycles of a month. The only data that is representative of the current number of students is the data for the three months when the field study was conducted, and therefore, this was the only data that was retrieved. A compilation of the average monthly data for the different areas is presented in Table 2.1. Something important to consider when looking at this data is that construction work, which requires large portions of water has been performed at the school during this time, which has increased the consumption substantially. This increase is mainly present in the living area for the students, as this is where the construction was performed for the time frame of the data collection. It is also important to note that this is only data of the usage of municipal water, and it does not include the water retrieved from the shallow well. However, the well only contribute to the water usage with very small volumes, as it is not very efficient. The increase in water consumption in the volunteers' and teachers' living area for the two later months can partially be explained by the addition of two more persons living there in the second and third month compared to the first.

Table 2.1: The consumption of municipal water for three different areas at the school between January and April 2025.

	Educational area [L]	**Residential area for teachers and volunteers [L]**	**Residential area for students [L]**	**Total**
11th of January to 11th of February	16 000	9 000	69 000	94 000
11th of February to 11th of March	31 000	19 000	66 000	116 000
11th of March to 11th of April	38 000	14 000	68 000	120 000

In the educational area, water is used in the classrooms, in the adjacent toilet building, and in taps installed right outside the school. Water there is used for sanitation, cleaning of the school building, and irrigation around the school. The residential area for volunteers and teachers covers household water needs for teachers, volunteers and farming animals. The water in the residential area for students is used for personal hygiene, dormitory activities, food preparation, irrigation, and during the time of the field study visit, also for construction of a new dormitory.

2.5 Wastewater management

Although the school is connected to the municipal water supply system, it is not connected to any wastewater treatment system. The existing wastewater network in Tabora is not very well functioning and only reaches around 2% of its inhabitants (Tabora Municipal Council, n.d.). Most of the water used at the school is therefore released into nature, completely untreated. However, there are three septic tanks at the site: one next to the toilets by the school, one next to the bathrooms by the students' dormitory, and one next to the volunteers' house. The water from all the toilets at the site is transported into these septic tanks, which are emptied every 2-3 years.

Water from showering, washing clothes, cooking and washing dishes is not transported to the septic tanks, and instead let out directly onto the ground at the site. The only exception for this is the greywater from one room in the volunteers' house, which is also transported into one of the septic tanks. Treating greywater is important, especially in non-sewered areas to reduce the risk of polluting the surroundings (Carden et al., 2008). It is also a waste of resources to not take care of it, as the greywater has potential of being reused for purposes like irrigation or construction work.

2.6 Stormwater management

During the rainy season, the geographical location of Tumaini Open School is prone to high intensity rainfall where a large volume of water enters a small area at the same time. The school's land area is surrounded by higher elevated land areas and a hill in the south and west, which tilts towards the school. This makes the catchment area during precipitation quite large for the school. Furthermore, the recent deforestation due to excavation of rock on these hills means that the flow of rainwater from this direction has increased in the last couple of years. Since the school's land is surrounded by lower lying land in the east, there is a slight tilt of the land area. This means that a lot of the rainfall is transported through the school area towards east at a fast rate. The stormwater is not properly managed at the site, and there are therefore large risks for floodings. The pluvial floodings, which have worsened in the last few years, have caused soil erosion to the roads in the area, and many of them are in such bad shape that they are no longer useable by vehicles. An example of a damaged road is seen in Figure 2.3. Although the roads are still available to travel on by foot, the damages complicate the transportation of building materials or other goods to and from the school. The school is yet to experience any damage on its buildings due to floodings, but it is not a scenario that can be ruled out from occurring in the future. On the most recently constructed building, the accommodation for volunteers, there is a drainage system of surface water. On the west side of the building, there are pipe inlets that transport stormwater underground and direct it out on the eastern side of the building. Since the school land slightly tilts towards the east, this is a way to prevent water accumulation along the buildings, which can lead to damage. This is the only building where some sort of drainage system is present as of now.

Figure 2.3: Road damaged though soil erosion caused by heavy rain.

2.7 Problems related to water

The school experiences three main problems related to water. The first problem is related to water supply sources and reliability. As the school regularly experiences shutdowns of the municipal water, which is their main water supply, the supply system is deemed unreliable. The backup plan of storing water in plastic tanks is one way to minimise the impact of the shutdowns, but as the population at the school increases, it will be more difficult to fulfil the increasing demand for water. Furthermore, the current water supply does not enable the usage of water for irrigation purposes during the dry season due to water shortages. Possible solutions for the water supply problem are to invest in drilling a borehole at the site to extract groundwater, install more plastic tanks, or to implement a RWH system. In this study, the focus is on the latter.

The second water-related problem is how floodings affect the area. Recent land use changes in the nearby area, possibly in combination with climate change has led to more extreme effects of rainfall. Although the problems up until now mostly have affected the roads, there is a possibility that buildings or other structures will be affected in the future. It is therefore necessary to examine if anything can be done to mitigate the effects floodings have at the site.

The third problem present at the school relates to how the water is managed. Even though the school can experience water shortages, water is not always treated very carefully and efficient. Many chances of reusing water for non-potable purposes like irrigation and construction work are not taken, and instead water is let out untreated into the surroundings. As the school strives to become self-sufficient and reduce their reliance on the municipal water supply system, a plan for how water could be managed better or reused needs to be made.

3 Theory

This chapter provides a comprehensive overview of the most important concepts and background information on the most essential parts of this study. It offers a more in-depth explanation of issues related to floodings and water scarcity, and explores the causes, effects, and the challenges they present. Furthermore, the chapter discusses potential solutions and management strategies aimed at mitigating these problems, including water treatment methods, greywater reuse, and water quality requirements. Together, these form the theoretical foundation for understanding the study's context and objectives.

3.1 Sustainability in water infrastructure

Sustainability in water management involves designing systems that meet the needs of both present and future generations by ensuring access to water resources while protecting and preserving the environment (Tsani et al., 2020). The design and implementation of water infrastructure must be resilient, efficient and adaptable to changing environmental and social conditions. This is particularly important in regions vulnerable to climate change.

Integrated water resource management (IWRM) is a framework for managing water resources in a way that balances social, economic and environmental aspects (Savenije & van der Zaag, 2008). It emphasises equitable access, sustainability, and efficient use of water resources. This approach is particularly relevant for rural areas where water scarcity, health challenges and resource limitations may exist. According to Savenije & van der Zaag (2008), the principles of IWRM highlights the importance of resource efficiency by ensuring that available water is managed to meet the needs of the user. The equity aspect means that the framework prioritises access to water for marginalised groups. IWRM also emphasise sustainability and promotes systems that can operate with minimal environmental impact and are resilient to climate variability. This case study applies IWRM principles to propose solutions that address both the immediate and long-term water requirements of the Tumaini Open School, while also considering the broader implications for the surrounding community.

3.1.1 Climate resilience in water infrastructure

Climate resilience refers to the ability of the water infrastructure to absorb, recover from, and adapt to climate-related shocks and stresses (Tortajada, 2016). As climate change leads to more intense and unpredictable weather patterns, it means that water infrastructure must be designed to handle both excess water and scarcity. A climate resilient water infrastructure ensures a stable and reliable supply by incorporating strategies such as diversification of water sources, increased water storage capacity, as well as flood- and runoff management (Asghari et al., 2023). Diversification of water sources entails that the reliance on a single water source is reduced by utilising other water sources such as RWH, groundwater extraction and greywater treatment. Increased water capacity can be achieved by constructing underground or insulated storage tanks to minimise evaporation losses and maintain water reserves during dry seasons. Flood and runoff management means diverting water or implementing controlled water collection systems to prevent excessive surface runoff. When managing water proactively, it is also important to understand the water levels and flow patterns in the system according to Asghari et al. (2023). This information can be provided from monitoring and data collection systems.

3.1.2 Sustainable water use and cost-effectiveness

Sustainable water use aims to balance the water consumption with the natural replenishment of water sources to prevent depletion and scarcity (Han et al., 2024). The purpose of effective management is to ensure that the water is used efficiently across all sectors such as drinking water supply, sanitation, and agriculture. This involves implementing strategies that minimise waste, promote reuse, and improve long-term cost-effectiveness.

Agriculture is the largest consumer of freshwater globally, which means that using efficient irrigation techniques is important to keep water losses minimal (Ferrero et al., 2024). An example of these techniques is drip irrigation, which delivers water directly to plant roots and significantly reduces runoff waste and evaporation losses. Drip irrigation also provides less risk for contamination when using recycled wastewater since the irrigation water is in direct contact with the crops. For sprinkler irrigation, there is instead a risk of evaporation of the water that is sprayed, which can create aerosols (Molle et al., 2016). Mulching can also be used to help retain soil moisture by limiting surface evaporation, while rainwater-fed irrigation systems maximise the use of harvested rainwater for crop production (Ferrero et al., 2024). Another important aspect of water use efficiency is leakage detection and infrastructure maintenance. Regular inspections of pipelines and storage tanks, the use of durable construction materials to reduce degradation, and the installation of water meters can help detect abnormal consumption patterns and prevent significant water losses (Ferrero et al., 2024). Leakages can account for 30-50% of total water loss in some developing regions, which makes proactive maintenance an essential part of water conservation (Kingdom et al., 2006).

Reducing the dependence on conventional water supply systems can improve sustainability and resilience, particularly in water-scarce regions (Rodrigues et al., 2023). RWH provides a low-cost and sustainable alternative to groundwater extraction and municipal water supplies. Capturing and storing rainwater reduces pressure on freshwater sources while providing an accessible supply for irrigation, sanitation, and, in some cases, drinking water. Similarly, greywater reuse can lower freshwater demand by treating and reusing wastewater from sinks, showers, and laundry for non-potable purposes (Rodrigues et al., 2023). Implementing greywater recycling systems in households and commercial buildings can significantly reduce water wastage, particularly in regions prone to facing water shortages. Both RWH and greywater management are described more in detail in later chapters.

Cost-effectiveness is a critical factor in sustainable water infrastructure, particularly in low-resource settings where funding for infrastructure projects is limited (EPA, 2025c). The goal is to maximise the benefits of water-related investments, which requires long-term planning and cost-efficient solutions that minimise operational and maintenance expenses. One important strategy is selecting high-quality, durable materials for water storage and distribution. Solutions requiring a higher initial investment can offer long lifespans, resistance to environmental stress, and minimal maintenance costs, which makes them cost-efficient investments over time (EPA, 2025c). Sustainable water infrastructure should also be designed for ease of maintenance to prevent costly repairs. For example, gravity-fed water systems, which rely on natural elevation changes to transport water, reduces the dependency on pumps and electricity, and lowers operational costs. Similarly, natural filtration methods, such as bio-sand filters and constructed wetlands, minimise the need for chemical treatment, and further reduces long-term expenses (EPA, 2025c).

According to Rodrigues et al. (2023), community involvement is another important aspect of cost-effective water management. Community-led initiatives, such as local water committees trained in basic maintenance and repair, can help reduce the reliance on external technicians and lower infrastructure maintenance costs. Additionally, using locally available materials for construction and repairs also minimises expenses while ensuring adaptability to local conditions (Rodrigues et al., 2023). Rural communities often rely on costly water delivery services during droughts (Asghari et al., 2023). Investing in on-site water storage solutions such as RWH systems and underground reservoirs, can significantly reduce reliance on expensive water supplies and enhance resilience during dry seasons. By integrating efficient water use strategies, alternative water sources, and cost-effective infrastructure planning, communities can achieve long-term water sustainability while reducing overall costs (Asghari et al., 2023).

3.1.3 Sustainable development goals

The United Nations 17 Sustainable Development Goals (SDGs) provide a blueprint for addressing global challenges, including water security, sanitation, climate change resilience and sustainable urban development (Tsani et al., 2020). In the context of sustainable water infrastructure, some of the most relevant Development Goals include SDG 3, SDG 6 and SDG 11. These are also the main SDGs related to this study, and a short explanation of them and their relevance is given below:

SDG 3: Good Health and Well-Being is a broad goal that includes several aspects. Access to clean water and sanitation is fundamental in public health as poor water quality and inadequate sanitation can contribute to the spread of waterborne diseases (United Nations, 2023). Sustainable water infrastructure can enhance public health by ensuring that communities have safe drinking water, improved wastewater treatment, and efficient flood protection to prevent contamination of water sources.

SDG 6: Clean Water and Sanitation aims to “ensure availability and sustainable management of water and sanitation for all” (United Nations, 2023). Addressing the goal requires solutions to capture, store, and treat water while also reducing water wastage. Implementing RWH systems and greywater management solutions can significantly improve water security and sustainability (United Nations, 2023).

SDG 11: Sustainable Cities and Communities aims to “make cities and human settlements inclusive, safe, resilient, and sustainable” (United Nations, 2023). Flood management is an important aspect to achieve this goal since floodings poses a significant threat to the safety and resilience of communities. By integrating flood mitigation strategies, urban and rural areas can become better protected from extreme weather events (United Nations, 2023).

3.2 Rainwater harvesting

RWH is the process of collecting, storing, and later using rainwater for water demanding activities (Campisano et al., 2017). The water can be collected from rooftops, paved surfaces or open catchment areas and is typically stored in tanks, reservoirs or depressions (Campisano et al., 2017; Malesu, 2006). RWH is a widely used technique in water-scarce regions, and it provides a sustainable alternative to groundwater extraction and other conventional water sources (de Sá Silva, 2022). Harvested rainwater has numerous applications depending on its treatment and quality (Campisano et al., 2017; de Sá Silva, 2022). Untreated rainwater is often used for irrigation, toilet flushing and cleaning purposes. With appropriate and sufficient treatment, it can also be used as a water source for drinking and cooking. In rural areas of Tanzania, access to reliable water sources is often limited due to inconsistent rainfall, and groundwater boreholes may be insufficient to meet water demands (Kimaro, 2019). RWH provides a practical and cost-effective solution to supplement water needs and enhance water supply (de Sá Silva, 2022). By collecting and storing rainwater during periods of heavy rainfall, resilience against dry seasons and potential water shortages can be improved. Furthermore, the impact of droughts on communities and agriculture can be minimised.

Sustainability benefits related to RWH include resource conservation, climate resilience, environmental benefits and cost-effectiveness (Mucheru-Muna et al., 2017). Resource conservation means that RWH reduces the dependence on groundwater and municipal water supplies and thus contributes to the preservation of water resources. Climate resilience entails that an adaptive solution is provided to cope with inconsistent rainfall patterns and prolonged dry seasons caused by climate change. According to Mucheru-Muna et al. (2017), direct environmental benefits are that surface water runoff is mitigated, which reduces soil erosion and prevents flooding in vulnerable areas. The cost-effectiveness aspect means that water bills are lowered, and the cost of water infrastructure is reduced.

Despite being a relatively clean source, rainwater can become contaminated through contact with collection surfaces and storage systems (Campisano et al., 2017). Common pollutants include physical contaminants such as dirt, leaves and debris (de Kwaadsteniet et al., 2013). Chemical contaminants in surface water include heavy metals and chemicals from roofing materials, while biological contaminants include pathogens from animal droppings or decaying organic matter. Iron occurs naturally in many water sources but can also enter rainwater from corrosion of metal pipes, roofs, or storage tanks (Artiola et al., 2012). High concentrations can affect taste, colour, and odour of the water. Nitrogen can occur in forms of nitrates and ammonia and can be picked up by water in the form of animal waste, decaying organic matter, or agricultural runoff (Oteng-Pepra et al., 2018). In excessive amounts, it may indicate contamination and pose risks to human health. Phosphorus is another nutrient often associated with runoff from detergents or fertilisers and can contribute to eutrophication in natural water bodies and lead to algae growth and disturbance of ecosystems (Badamasi et al., 2019). From collection surfaces like roofs, it is especially the first flush of rain that becomes polluted. Yaziz et al. (1989) noticed that the first samples of rainwater from a roof contained high concentrations of microbiological contamination, while the samples collected after 5 L were completely free from contamination of faecal coliform. Harvested rainwater is usually stored in water storage tanks. These can become breeding spaces for mosquitos if they are not properly maintained, as mosquitos are drawn to standing water (de Kwaadsteniet et al., 2013). According to de Kwaadsteniet et al. (2013) rainwater should undergo treatment to ensure safe water use. This may include filtration to remove debris or particles, sedimentation to allow particles to settle, or disinfection with chlorine or ultraviolet (UV) light to kill pathogens.

Several methods can be implemented to harvest and store rainwater effectively, including surface runoff collection, roof catchments, storage tanks, percolation pits and recharge wells (Uppala & Dey, 2021). Surface water collection is used to capture water from open surfaces such as yards or roads and directing it to reservoirs and ponds. Roof catchments utilise gutters and pipes to direct the rainwater to storage tanks. According to Uppala & Dey (2021), storage tanks are used to store harvested water above ground or underground, and can be made of materials such as concrete, plastic, fiberglass, or stainless steel, depending on availability and budget. Percolation pits and recharge wells direct the harvested rainwater to recharge groundwater aquifers to enhance the local water availability. For this project, harvesting rainwater from roof surfaces and directing it to a storage tank was seen as the preferrable solution beforehand, and therefore, this is what the rest of this chapter will focus on.

3.2.1 Storage tank materials

The material selection for water storage tanks is important to ensure durability, water quality and cost-effectiveness in RWH systems. Different materials provide benefits in terms of longevity, maintenance, thermal properties, and resistance to environmental factors. In the context of rural Tanzania, where high evaporation rates and extreme weather conditions pose challenges to water conservation, selecting the most suitable tank material is crucial for the long-term sustainability of water storage infrastructure (UNESCO, 2019).

Concrete tanks
Since Tanzania experiences high evaporation rates, an underground or partially buried concrete tank can significantly reduce water loss by limiting the exposure to direct sunlight (UNESCO, 2019; Wagh et al., 2021). The thermal mass of concrete also provides good insulation to maintain cooler water temperatures, which in turn minimises algae growth, which is an issue commonly associated with above-ground plastic tanks (Ozyildirim et al., 2024). Additionally, once constructed, concrete tanks require minimal maintenance, which reduces the long-term costs of repairs and part replacements (Shalgar, 2024).

Concrete tanks have several benefits when it comes to water storage, including durability, cost-effectiveness, and resilience to environmental challenges (Shalgar, 2024). They have a long lifespan and can endure harsh weather conditions, which makes them a reliable option for long-term water storage. Additionally, concrete tanks are highly resistant to sunlight as opposed to plastic tanks, which are susceptible to degradation from prolonged UV radiation exposure (Shalgar, 2024; Dyagelev & Astrakhantseva, 2025). One of the primary advantages of concrete tanks in Tanzania is the availability of local materials and labour (Kihila, 2014). The use of locally sourced concrete lowers construction costs compared to importing high-quality plastic or metal tanks. Additionally, employing local labour for construction fosters economic benefits within the community and ensures that maintenance skills remain accessible at the local level (Wells & Hawkins, 2018).

Despite the advantages, there are also several negative aspects of using concrete tanks. One potential drawback is their susceptibility to cracking, which can lead to leakage if not properly sealed or maintained (Kihila, 2014). This risk is particularly prominent in underground tanks situated in clay soil. While leaks can be repaired relatively easily, it may be necessary to drain the tank when conducting the reparation. To mitigate the risks for cracks and seepage occurring in tanks, waterproof coatings or reinforced concrete could be used (Khanna et al., 2024). Concrete water storage tanks tend to increase the pH level of stored water due to the leaching of calcium compounds from the cement, which can help neutralize rainwater that tends to be slightly acidic (Nwoke, 2019). However, excessive leaching can lead to mineral buildup on the surfaces of the tank and in the water. Additionally, concrete surfaces can result in microbial contamination from bacterial growth in cracks or porous sections of the tank, which can lead to an increase in heterotrophic bacteria in the storage tank.

Plastic tanks

Plastic tanks are typically made from polyethylene (PE) and polypropylene (PP) and are widely used for RWH due to their affordability, durability and resistance to various environmental factors (Muhsin & Al-Tabatabai, 2024). PE and PP materials are suitable for water storage due to their chemical stability and low risk of contaminant leaching. Plastic tanks are generally very lightweight compared to tanks made from other materials, which allows for relatively easy transportation and installation with minimal labour, hence their cost-effectiveness (Tiwari & Torgal, 2019). Plastic tanks are also resistant against rust and corrosion, unlike metal tanks that may require rust-proofing treatments. This is a significant advantage, as it reduces maintenance costs and extends the lifespan of the tanks (Feng et al., 2019). Also, plastic tanks do not require sealing, internal coatings or treatments to maintain water quality (Arunkumar et al., 2023).

Plastic tanks may, however, be vulnerable to sunlight and heat, since prolonged sunlight exposure can cause plastic to degrade over time, which can lead to potential structural weakness (Nzimande et al., 2024). Regarding structural strength, plastic tanks are also prone to punctures and can be damaged by heavy impacts or extreme weather conditions (Bobyr et al., 2024). Harsh weather and high temperatures can also force plastic tanks to introduce chemical contaminants over time (Nwoke, 2019). Several plastic materials degrade under exposure to heat and sunlight and releases harmful substances such as bisphenol A or microplastics. If not properly covered, plastic tanks can also allow light to penetrate, which can promote algae growth in the stored water (Artiola et al., 2012). Water stored in plastic tanks tends to have lower dissolved metal content compared to concrete or steel tanks. However, according to Nwoke (2019), the water in plastic tanks can still experience significant bacterial contamination due to temperature fluctuations.

Metal tanks

Metal water tanks are often made from galvanised steel, stainless steel, or aluminium, and are generally more robust than plastic tanks (Meier, 2010). They have a long lifespan and can withstand external pressure, which makes them less prone to damage and deformation in extreme weather conditions (Bobyr et al., 2024). Additionally, metal tanks have a higher structural integrity, which allows them to hold larger volumes of water than the alternatives without the risk of bulging or deformation over time. Another advantage is recyclability and sustainability since metal water tanks, especially tanks made from aluminium or steel, can be recycled at the end of their lifespan (Steel Technology, n.d.). This makes them a good option from an environmental aspect. Since metal tanks prevent light penetration, it also means that they significantly reduce the risk of algae and bacterial growth inside the tank (Yeh et al., 2011).

A limitation of metal tanks is the risk of corrosion. Unless they are treated with a protective coating, metal tanks are highly susceptible to rust and corrosion, particularly in humid or saline environments (Gilbreath, n.d.). Corrosion can lead to increased concentrations of heavy metals such as iron, manganese, and zinc into the water, which increases the total dissolved solids and conductivity (Nwoke, 2019). Over time, this can result in water discoloration, metallic taste, and potential health hazards if toxic metals like lead or chromium are present in significant concentrations. Corrosion rates are highest at around 30°C and coincide with the highest bacterial growth. Metal tanks also come with a much higher initial cost compared to tanks from other materials and are generally more expensive both in terms of material cost and installation (Roncetti, 2011). There are also challenges related to weight and installation since large metal tanks require professional installation and may need additional support structures, which increases the overall costs (Scott, 2015). Additionally, the thermal insulation properties of metal tanks are not very good on their own (Lide, 2003). Metals are good heat conductors, which means that they can quickly transfer heat from the outside environment to the inside of the water tank, or vice versa. This can lead to significant temperature fluctuations in the stored water, which in turn can affect the quality of the water.

3.2.2 Placement of water storage tank

To maximise efficiency and accessibility to the water storage tank, it should ideally be placed strategically based on the proximity to water collection points, the elevation relationship between points of collection and distribution, and accessibility for maintenance and water use. When it comes to proximity to water collection points, the tank should be positioned near the RWH system, such as a central building with a large roof area, to allow easy and direct water flow into the tank (Li et al., 2020). A slight elevation near the roof drainage system would improve gravity-fed water collection and thus reduce the need for additional pumping infrastructure (Ghadage et al., 2016). If feasible, the tank should also be placed slightly uphill from the main water distribution points so that water can be distributed via gravity, which reduces or even eliminates the need for pumps. A raised or elevated tank can also improve water pressure for distribution.

If the tank is to be located above ground, it should be placed in a shaded area to minimise loss of water through evaporation (Zeadeh et al., 2024). Planting trees or constructing a roof over the tank could be ways to help provide shade. A partially or fully buried tank would further reduce evaporation and maintain a more stable water temperature, which prevents microbial growth (Slavik et al., 2020). The tank should also be easily accessible for periodic maintenance, cleaning, and water retrieval and be close to the most important water usage points such as agricultural plots to minimise water transport distances (Manga et al., 2021).

To avoid contamination of the stored water, the tank should not be placed near sources of contamination such as latrines, waste disposal areas, or agricultural runoff areas to prevent water quality issues (Manga et al., 2021). Proper drainage should be considered to prevent stagnant water buildup in the surrounding areas around the tank. The placement of a water storage tank in relation to a septic tank is also something that needs to be considered. To avoid infiltration of contaminated waste from a septic tank into a water storage tank, the two should not be placed near each other (Nnaji & Nnam, 2019). The water tank should also be placed at a higher elevation than a septic tank to avoid contamination through runoff or infiltration. Furthermore, to avoid microbial contamination, a water harvesting tank should not be placed in an area where domestic animals roam freely, partly because of possible contamination on catchment areas like roofs, but also due to possible seepage of animal droppings through the surrounding soil. Guidelines provided by United Republic of Tanzania (2007) states that water points should not be placed closer than 150 m from graves and 50 m from septic tanks. It is therefore important to consider the proximity to potential pollution sources when deciding the placement of a water storage tank.

3.2.3 Design of pipe system

A conveyance system is essential for effectively transporting rainwater from the roof catchment area to the storage tank (Khoury-Nolde, 2010). These systems include gutters, downspouts, and drainpipes that direct the collected water through a filtering system before reaching the storage tank. According to Khoury-Nolde (2010) The materials used for the pipework should be durable, non-toxic, and resistant to corrosion. Commonly used and suitable materials for this purpose include polyethylene (PE), polypropylene (PP), and stainless steel since they ensure safe water transport and longevity. Properly fitted and maintained gutter and pipe systems can significantly improve rainwater collection efficiency. Other pipe material options such as cement-based products, bamboo, and wood can also be used, depending on the availability and local preferences (Khoury-Nolde, 2010). According to Still & Thomas (2002) a minimum gradient of 1% is recommended to ensure proper water flow in pipes and gutters and reduce the risk of water pooling and debris accumulation.

To handle the peak runoff rate, gutter and pipe sizes must be chosen so that their flow capacity exceeds the peak flow rate to prevent overflow (North Carolina Department of Environmental Quality, 2017). The hydraulic capacity depends on the pipe diameter, slope, roughness coefficient, and shape. The peak flow from a catchment area is calculated using the rational method shown in Equation 3.1 (North Carolina Department of Environmental Quality, 2017; Myronidis, 2017).

$$Q = 0.278 * C * A * i \tag{3.1}$$

Where:
Q = peak flow rate (m^3/s)
C = runoff coefficient (dimensionless)
A = catchment area (ha)
i = rainfall intensity (mm/hr)

3.2.4 Material of collection surface

The material of the collection surface, for example a roof, can have a large effect on the quality of the collected water. Lee et al. (2012) found that galvanised steel was the preferred material for RWH as it achieved sufficient quality for drinking water compared to roofs made of wooden, concrete, or clay tiles. One explanation for this could be that the other materials are more porous, which can lead to contaminants being trapped or mosses growing, which affects the water quality negatively. Similarly, Chang et al. (2004) found that runoff water from wooden roofs were the most polluted, when compared to roofs made of galvanised iron, painted aluminium, and composition shingle. This was also due to the structure of the material as wood can trap leaves or other debris and has a risk of growing fungi or mould if it is not properly dried. However, Lee et al. (2012) also found that the galvanised steel had the highest concentration of metals and total suspended solids (TSS) in water samples of the first flush of a rain activity. This highlights the importance of not collecting the first portion of water reaching the collection surface. Furthermore, they found that galvanised steel roofs performed best in terms of low concentrations of faecal contamination, with no pathogens at all in samples taken from the first flush.

Another surface material with significant advantages for rainwater collection is stainless steel (Müller, 2015). Unlike galvanised steel, stainless steel does not leach zinc or other metals into the water and can thus reduce contamination risks. The surface of stainless steel is also non-porous and smooth, which minimises bacterial growth and accumulation of debris, and can thereby improve water quality (Pathirajah et al., 2022). According to Müller (2015), stainless steel is highly resistant to corrosion, even in environments with high acidic rain or high humidity where other metals may degrade over time. Furthermore, it is a durable and low-maintenance material, since it does not require protective coatings nor frequent replacements.

3.2.5 Water cleaning and filtration

Another aspect to consider in the design of a RWH system is how the quality of harvested rainwater can change during storage. Water that is stored for long periods in tanks is susceptible to microbiological, chemical, and physical degradation (Nwoke, 2019). Poor mixing within the tank can result in stagnation of the water, which can lead to bacterial growth, sediment accumulation, and chemical interactions between the water and the tank material. Over time, prolonged water storage can result in increased levels of dissolved solids, heavy metals, and microbial contamination. Additionally, tanks can serve as entry points for contaminants (Nwoke, 2019). Poorly sealed hatches, vents, and pipe joints can allow debris, dust, or organic matter to enter, which could lead to further water quality degradation. Furthermore, the type of tank material plays an important part in how water quality changes over time.

There are several methods for cleaning and filtrating the rainwater before it enters the harvesting system, one of which are first-flush diverters (Charlebois et al., 2023). They ensure that the initial runoff, which often contains the highest levels of contaminants, debris and particles, is redirected and diverted from the water storage tanks. Another effective method is pre-filtration, which involves using simple mesh screens or sediment filters at the water collection point (Mohammed et al., 2011). This is done to remove debris such as leaves and dirt before the water enters the water storage tank.

There are also more extensive pre-filtration methods that require additional tanks and thus more resources and space. According to Mohammed et al. (2011), layers of gravel, sand or charcoal can also serve as a filtration step in a pre-filtration unit to further improve the water quality in the tank. Coagulation and sedimentation are effective methods of removing fine particles from collected water. The water is left to settle, which allows suspended solids to sink to the bottom in a separate settling tank for removal (O'Melia, 1998). To improve the sedimentation process, coagulants such as alum can be added to help particles clump together, which allows them to settle more quickly. An additional method is slow sand filtration which uses layers of sand, gravel and biofilm to remove bacteria, parasites, and organic matter from the water (Abdiyev et al., 2023). This filtration process is highly effective and requires minimal maintenance, which makes it ideal for rural areas where access to advanced treatment may be limited.

Boiling water is an effective way of killing bacteria and viruses to significantly improve the water quality (Karim et al., 2023). Furthermore, solar disinfection is also a way of improving the quality. The method utilises sunlight to purify water by collecting it in transparent plastic containers and exposing it to direct sunlight for several hours, during which pathogens are killed from UV radiation. Another treatment method is chlorination which involves adding chlorine or bleach in controlled amounts to disinfect the water and kill harmful microorganisms (Latif et al., 2023). However, this treatment requires careful dosage to ensure effective water purification while avoiding leaving harmful chemical residuals in the storage tank.

3.3 Hydrological modelling

Hydrological modelling plays an important role in understanding and predicting how rainfall interacts with the landscape, which influences runoff, infiltration and flood risks (Devia et al., 2015). Hydrological models provide valuable insights into water flow dynamics, which is beneficial when planning and designing water management systems to prevent flooding and optimise RWH (Mazzoleni et al., 2017; Campisano et al., 2017). By simulating precipitation events over a given area, hydrological models can predict how the water will distribute across the landscape and can thus identify areas prone to flooding (Mazzoleni et al., 2017). The interaction between rainfall and the landscape is determined by several key factors including rainfall intensity, duration, and frequency, which are all inputs that influence how much water reaches the ground and how quickly it accumulates (Sikorska et al., 2018). When the rainwater reaches the surface, its movement is affected by the characteristics of the terrain.

Soil properties such as permeability, porosity, and infiltration capacity influence how much water is infiltrated into the ground. Densely vegetated areas can slow runoff and promote infiltration, while impervious surfaces such as roads and concrete lead to higher runoff rates and increased flood risks (Devia et al., 2015). Additionally, the slope of the land influences the water flow since steeper gradients accelerate runoff while flatter areas allow for a higher degree of infiltration and water retention (Aksoy et al., 2016). There are several methods to measure the infiltration of soil in field studies. Zhao et al. (2019) compared the constant head single ring infiltration (CHSRI), the falling head single ring infiltration (FHSRI), and the double ring infiltration (DRI) tests in field to laboratory results and found that the DRI test showed the most accurate results. Using the DRI instead of an SRI test gives a more accurate result of the vertical infiltration as the outer ring prevents the water from the single ring to infiltrate horizontally (Gregory et al., 2005). Using the DRI test, the infiltration can either be measured with the constant head method, where the water level is kept at a constant level and the time and added volumes of water while water is seeping is noted. It could also be measured by using the falling head method, where the time it takes for a filled waterhead to empty is measured. Although there are field methods that give more accurate results, like ponding in large areas, cylinders can be used as a cheaper and more convenient way to measure the infiltration of a soil (Johnson, 1963). When performing a DRI test, it is suitable for the outer ring to have twice as large diameter as the inner ring, and suitable dimensions of the rings are diameters of 30 and 60 cm (Johnson, 1963; ASTM International, 2018).

Topographic data is another important input when modelling water movement across landscapes (Aksoy et al., 2016; Hawker et al., 2022). Information on the topography could be described as a digital elevation model (DEM), or a digital terrain model (DTM) (Wing & Frank, 2011). DEMs represent the elevation of the terrain, typically excluding vegetation and buildings, while DTMs represent the bare ground surface, including both natural and constructed man-made features (Wing & Frank, 2011; Hawker et al., 2022). These elevation models allow researchers to simulate how water flows, accumulates, and infiltrates into the ground (Hawker et al., 2022). The accuracy of these models largely depends on the resolution of the collected data. On a global scale, DEMs often have information at a 1-arc grid spacing, which is approximately equivalent to a 30 m grid spacing (Hawker et al., 2022). The grid spacing is defined as the density of measuring points, and for a 30 m grid spacing, it means that elevation data is recorded in grid points every 30 m. The resolution of these DEMs can be substantially improved by merging the data from the DEMs with global positioning system (GPS) data collected via surveying (El Mhamdi et al., 2024). A 30 m grid spacing can be sufficient for large-scale assessments but may not be able to capture finer topographic variations for more detailed hydrological studies. Merging DEMs with GPS data can therefore be useful when performing hydrological modelling since the accuracy of the information on the flow pattern of the water can be significantly improved.

Geographic Information Systems (GIS) software is commonly used to process DEMs and to integrate rainfall data, soil properties, and land cover information to create detailed simulations of hydrological processes (Devia et al., 2015). Through accurate hydrological modelling, urban planners and researchers can better predict flood events, optimise drainage systems, and enhance water resource management. As technology constantly advances, it means that increasingly sophisticated modelling techniques, which can incorporate real-time data and machine learning algorithms, continue to improve the accuracy and applicability of hydrological predictions.

3.3.1 Collecting topographic data

There are several methods that can be used to collect input data for creating DEMs, and one of them is to collect data with a GPS receiver device. The process of the method is that orbiting satellites sends signals to the GPS receiver, which then processes these. By using the speed of light constant, the distances between a satellite and a GPS receiver can be calculated to output horizontal and vertical positioning data of a measure point (Wing & Frank, 2011). Fry et al. (2015) used a handheld GPS device to collect elevation data in mountainous areas where elevation data was unavailable, to generate DEMs with a higher resolution than 30 m. The method can be questionable when measuring absolute elevation, however, relative elevation is believed to be accurately measured. This is important, for example when mapping how water flows in an area. According to Fry et al. (2015), the GPS data collection method was proven cost-effective as it resulted in relatively high-resolution maps at a low cost.

Another method that could be applied is gathering elevation data through electronic distance measurements, which uses trigonometric principles to determine differences in elevation between measured points (Wing & Frank, 2011). However, even though this method can provide precise results, it is very time consuming and requires a clear line of sight (LOS) between measurement points, which makes it an unsuitable method for heavily vegetated areas. There are more advanced methods that result in very accurate results of elevation data, for example light detection and raging (LiDAR) and unmanned aerial vehicle (UAV), although they are very costly to use (Fry et al., 2015). Wing & Frank (2011) argues that a land of thousands of hectares is needed for LiDAR and UAV to be cost-effective, hence it is not a suitable solution for smaller areas.

To successfully perform an accurate land survey by collecting global navigation satellite system (GNSS) data, it is necessary to consider the availability and movement of the satellites. GNSS is the collective name for different satellite systems that provide geographical position data (Dutta et al., 2023). These include the American GPS system, which is the most widely used, Europe-developed Galileo and Russia-developed GLONASS among others. These three are also the most prominent satellite systems operating in Africa (Dodo & Kamarudin, 2007). One factor that affects the accuracy of GNSS data collection is the canopy of the landscape where the data is recorded (Fauzi et al., 2016). If an area is covered with multiple buildings or trees, it can prevent signals from satellites to reach the receiving GPS. Furthermore, the satellites that are sending out signals constantly orbits around earth. This means that the satellite geometry, which consist of the satellites available for receiving and sending signals, change depending on the time of day. Wing & Frank (2011) states that a GPS receiver needs to secure signals from at least four satellites to sustain an accurate positioning result. The time and day of data collection is therefore important to consider when striving for accurate results. However, the most prominent challenge with collecting accurate positioning data is the multipath effect (Xue et al., 2022). This effect arises when the satellite signals bounce off nearby trees or buildings before reaching the receiver, which can decrease the accuracy of the position measurements. This effect is mostly present in urban areas with tall buildings or in heavily vegetated areas with many trees or bushes.

Fauzi et al. (2016) investigated the difference in vertical position accuracy between GNSS-enabled smartphones or tablet phones and a handheld GPS. Although the mobile phones did provide sufficient vertical position data, the errors associated with the data collected with the handheld GPS were smaller. A handheld GPS was therefore recommended to use when requiring more accurate results, especially in heavily canopied areas, as the difference in performance there varied greatly.

3.4 Flood mitigation strategies

The purpose of flood mitigation strategies is to control and manage the volume and flow of excess water during heavy rainfall events and thus reduce the risk of water damage to infrastructure and ensure a safer environment (Haasnoot et al, 2011). Several techniques can be used in flood prone areas based on the site's characteristics and hydrological conditions (Raspati et al., 2017). Some examples include infiltration basins, retention ponds, swales, and green infrastructure solutions. Sustainable urban drainage systems (SUDS) are stormwater solutions that not only prioritise the management of stormwater but also focus on improving quality of stormwater and utilising natural processes like filtration, evapotranspiration, reuse, and retention. (Rathnayake & Srishanta, 2017). Using SUDS instead of conventional drainage systems can also be a way to save money as conventional drainage systems are costly to construct and manage. The economic and environmental benefits experienced when using SUDS means that this was prioritised for this project.

An important aspect of SUDS is green infrastructure. Green infrastructure is a nature-based approach to water management by mimicking natural processes to manage surface water (Green et al., 2021; Uthirakrishnan et al., 2022). These solutions can provide ecosystem services and improve biodiversity in both rural and urban areas (Green et al., 2021). Green infrastructure includes constructed wetlands, permeable surfaces, bioswales, and rain gardens. Constructed wetlands are engineered systems designed to treat and manage stormwater and greywater through natural filtration in vegetative water bodies (Raspati et al., 2017). They provide multiple benefits, including water purification through biological treatment, biodiversity enhancement and flood control by slowing down water (Uthirakrishnan et al., 2022). Permeable surfaces allow water to infiltrate through the surface instead of generating runoff (Raspati et al., 2017). Examples of permeable surfaces include porous asphalt, permeable concrete or interlocking pavers. These solutions reduce the surface runoff and help to recharge the groundwater, which puts less pressure on drainage systems. Bioswales are similar to swales but are more engineered, often incorporating vegetation that absorbs and filter surface water (Raspati et al., 2017). Rain gardens are shallow, landscaped areas planted with vegetation that capture and infiltrate surface water. The methods provide both aesthetic and ecological benefits, and they remove pollutants through soil filtration and plant uptake (Raspati et al., 2017).

3.4.1 Swales

Swales are shallow vegetated channels that direct and slow down the flow of stormwater runoff (Raspati et al., 2017). They distribute water across the landscape, reduce risks of localised flooding and promote infiltration. The vegetation in swales also helps filter pollutants from the water. According to Raspati et al. (2017), swales are most suitable in rural areas where they can be integrated into the existing landscape. Mhina & Mapinduzi (2024) states that swales are one of the most suitable stormwater management strategies to implement on a smaller scale like a plot or neighbourhood level. They are often used to catch stormwater runoff from roads, and they can be covered in vegetation that absorbs water. They are most effective at relatively flat sites and the infiltration rate in the soil should be over 12.7 mm/h for them to achieve the best results. Wu & Allan (2018) found that swales along the roadsides can be an efficient way to reduce the pollutants in road runoff. Additionally, Lucke et al. (2014) found that TSS and total phosphorus are two pollutants that can be effectively reduced from stormwater passing through swales. However, it is important to note that swales are more effective for catching larger particles compared to small. Therefore, swales should be seen as a pretreatment and should preferably be combined with other treatment methods if the main objective is to treat stormwater. However, for only reducing stormwater runoff volumes, swales have proven efficient, as Lucke et al. (2014) found the mean flow reduction to be 52%, and even higher for peak flow reduction.

3.4.2 Infiltration basins

Infiltration basins are shallow depressions designed to capture surface runoff and allow water to infiltrate into the ground (Raspati et al., 2017). The basins help reduce peak runoff volumes, mitigate floodings and improve water quality by filtering pollutants as water percolates into the soil. However, it is important to pretreat the stormwater entering and to maintain the system for it to work efficiently. According to Raspati et al. (2017), infiltration basins are particularly effective in areas with permeable soils that support groundwater recharge. The soil should have an infiltration rate of 7 to 13 mm/h, and the system is suitable in areas smaller than 4 ha.

3.4.3 Retention ponds

Retention ponds are permanent water bodies that collect and store runoff for extended periods (Raspati et al., 2017). Unlike infiltration basins, retention ponds are designed to hold water after rainfall events and gradually release water into the surrounding environment. They are effective for managing large volumes of water, reducing peak flows and providing a habitat for wildlife. Proper design and maintenance are required to prevent stagnation and ensure effective operation (Raspati et al., 2017). In addition to taking up a lot of space, retention ponds can also attract mosquitos if the water is stagnant.

Retention ponds are usually not used to capture water only from a plot, but rather from a whole neighbourhood or even a larger area (Mhina & Mapinduzi, 2024). Bio retention cells are more common when designing a solution for a smaller area. The preferred size for the catchment area of retention ponds is at least 4.5 ha, and the infiltration rate of the soil should be more than 12.7 mm/h (Swilla et al., 2024). Rain gardens, which are a type of bioretention ponds, can be an alternative suitable for smaller areas, and has no requirements on infiltration rate in the soil.

3.5 Greywater management

Treating greywater from households on site to recycle it for non-potable purposes is one way to minimise the usage of drinking water (Maiga et al., 2024). It is therefore a solution to consider implementing in areas experiencing water scarcity. Greywater is defined as the wastewater from households, with an exception for the wastewater from toilets or the kitchen, which instead is referred to as black water (WHO, 2006). Greywater includes water from showers, sinks, and washing machines. Due to the varying activities greywater can originate from, the quality of the water can differ. Pollutants that are likely to be found in greywater are organic matter, nutrients like phosphorus and nitrogen, metals, and many micropollutants. Furthermore, other physio-chemical parameters that can distinguish greywater from clean water are the temperature, pH, suspended solids, and turbidity. The turbidity and the total amount of suspended solids is generally high for greywater that has been used in laundry. Since greywater excludes water from toilets, the faecal contamination is usually low, although it can still be present (Uthirakrishnan, 2022). The sources of this are believed to be from washing nappies and direct contact with water after using a toilet.

3.5.1 Treatment methods for greywater

As greywater can be contaminated with various contaminants, it is not ideal to dispose of untreated greywater into the environment. There are several methods available to treat greywater, and depending on the dominating pollutants in the water, some methods work better than others (Oteng-Peprah et al., 2018). The choice of method depends on whether the water is treated on or off site, and if it should be treated for potable or non-potable purposes. The different methods can be divided into physical, chemical, and biological (Awasthi et al., 2024). The physical and chemical methods are sometimes also combined and then referred to as physiochemical (Oteng-Peprah et al., 2018). These consist of physical and or chemical treatment methods like filtration or adsorption while the biological treatment methods use microbes, oxygen, and sunlight to remove contaminants. Some examples of biological treatment methods are activated sludge systems, rotating biological contractors, and membrane bioreactors.

Sand filters are one of the most common treatment methods for greywater, but there are also other types of filters that can be used. Dalahmeh et al. (2012) studied the effectiveness of four different filters in removing pollutants from greywater to ensure sufficient water quality to reuse it for irrigation purposes. The four types of filters that were investigated were bark, activated charcoal, polyurethane foam and sand, and the two first options were proved best at removing pollutants like organic matter, phosphorus, nitrogen, and microorganisms, which are common pollutants in greywater.

A simple and low-cost method for greywater treatment is to use a layered filter system composed of gravel, sand, and optionally, activated charcoal (Solihu et al., 2022; Dalahmeh et al., 2012). This type of system is especially suitable for rural areas where access to more advanced or expensive equipment may be limited. The solution consists of a barrel filled with successive layers of coarse gravel, fine sand, and a top layer of charcoal (Dalahmeh et al., 2012). According to Solihu et al. (2022), the gravel removes large particles, the sand removes suspended solids and turbidity, and the charcoal absorbs organic matter, odours, and some pathogens and chemicals. The greywater is poured into the top of the unit, percolates down through the filtration layers, and is collected at the bottom (Solihu et al., 2022; Dalahmeh et al., 2012). The system is not suitable to produce water for drinking or hand washing, but it can make greywater safe for non-potable uses such as irrigation, flushing toilets or washing outdoor surfaces. A case study from Karagwe, Tanzania by Shrestha (2017), demonstrates the use of this type of filter at a daycare centre. The proposed system consisted of a multi-barrel setup with sedimentation, sand, and charcoal filters arranged in sequence. The greywater was primarily from hand washing and the treated water was used for toilet flushing. The study emphasised the low cost, availability of materials, and simplicity of construction and maintenance, which makes it a feasible solution in similar rural settings. Another successful implementation was reported by Samal et al. (2020), who tested a pilot-scale filter system in Nepal using layered gravel, sand, and activated carbon to treat household greywater. The system reduced biochemical oxygen demand, chemical oxygen demand, and TSS by over 85%, and the treated water met standards for irrigation. The setup was housed in a plastic barrel, used readily available local materials, and required minimal maintenance.

Another treatment method is constructed wetlands, where greywater is treated when transported through a wetland. Maiga et al. (2024) tested this solution in a household in rural sub-Saharan Africa and the study showed great efficiency in removal of organic matter, and a relatively high efficiency rate of microbials. The removal of nutrients was also considered sufficient with a removal rate of over 60%. However, the study concluded that the removal of nutrients can be unnecessary if the reuse purpose of the greywater is irrigation, as the nutrients can act as fertilisers for the soil. Overall, Maiga et al. (2021) recommends this treatment method for treating household greywater in similar cases where developing regions or countries experience water scarcity. Abunaser & Abdelhay (2020) found the constructed wetland method effective when implementing it in rural areas of Jordan as the treated water fulfilled quality guidelines set for water used in irrigation. In their treatment system, the constructed wetland was preceded by a pretreatment including a sedimentation tank to remove solid particles and a separation barrel to remove grease and fat.

An alternative to traditional constructed wetlands is the elevated filtration bed, which mimics the natural filtration processes of wetlands but is constructed above ground level (Morandi et al., 2021). These systems typically consist of a bed filled with porous media such as gravel, soil, and sand, which are planted with vegetation. Greywater is added at the top or from the side of the system and passes vertically or horizontally through the media layers, where contaminants are removed through a combination of physical filtration, microbial degradation, and plant uptake (Morandi et al., 2021; Carballeira et al., 2021). The treated water is then collected at the base and can be reused for non-potable purposes such as irrigation or toilet flushing (Abunaser & Abdelhay, 2020). The system can be classified as a constructed wetland, but its key distinction is that its elevation is above ground level. This design choice allows for gravity-fed operation, simplifies maintenance access, and reduces risks of mosquito breeding by preventing surface pooling (Morandi et al., 2021). Elevated beds are especially well-suited for sites with limited ground permeability or areas prone to waterlogging, as they avoid direct infiltration into the surrounding soil and allow for more controlled water management.

One of the main benefits of elevated plant filtration beds is their adaptability to rural contexts with limited technical infrastructure. The construction relies on inexpensive and locally available materials such as gravel, sand, and wooden or brick containment structures (Sijimol & Joseph, 2021). The plants can often be sourced locally and should ideally be species that tolerate alternating wet and dry conditions. The systems also operate passively, and do not require any electricity or complex machinery, which makes them well aligned with the needs of low resource areas (Sijimol & Joseph, 2021). Several studies have confirmed the long-term effectiveness of planted soil beds when treating greywater. For example, Sasse (1998) and Pinto et al. (2010) found that horizontal planted filters can remove over 90% of suspended solids and significantly reduce faecal coliform concentrations, provided that the systems are not hydraulically overloaded. These findings emphasise the reliability of passive planted systems in achieving significant contaminant removal, even in decentralised or low-resource settings. Their relatively low cost and lack of energy requirements make them particularly suitable for rural institutions such as schools. However, some limitations must be considered. Pre-treatment is necessary to remove detergents and larger particles that could clog the system (Abunaser & Abdelhay, 2020). Furthermore, regular inspections are needed to check for clogging, plant health, and flow distribution. In areas with long dry seasons, supplementary watering of the plants may be needed to maintain vegetation cover and system performance.

3.5.2 Public acceptance and willingness of reusing greywater

A challenge with reusing greywater can be how the users perceive the water. Bautista Quispe et al. (2025) examined the willingness of students at a rural school experiencing water scarcity to reuse greywater and found that 88% of them had a positive attitude. The students were willing to reuse greywater for activities such as cleaning, irrigation, toilet flushing, and most commonly hand washing. These results differ from other studies which have shown higher acceptance in reusing greywater for activities where no direct contact between humans and the water is required, like agricultural purposes or flushing toilets (Al-Khatib et al., 2022; Bakare et al., 2016).

The treatment method applied to clean the greywater can affect the acceptability of greywater reuse purposes. Al-Khatib et al. (2022) found that no treatment, or an on-site treatment of greywater had a lower acceptance rate than reusing greywater treated in a centralised system. For the first two options, the only reuse purpose seen as accepted was bush irrigation (62,6% and 62,3% acceptance), while for treating water in a centralised treatment plant, both bush (73,6% acceptance) and crop (62,3% acceptance) irrigation were seen as accepted. The acceptance for purposes requiring direct contact with humans like drinking, washing food or flushing toilets was very low, while other purposes not requiring direct contact like cutting stones or using water for construction was moderately accepted (Al-Khatib et al., 2022).

Bautista Quispe et al. (2025) found in their study that the main apprehensions with reusing greywater were the concern of health risks connected to it and the quality of the water regarding looks, smell, and taste. In contrast, Bakare et al. (2016) found that more than 60% did not believe that there are increasing health risks when reusing greywater and only 20% are concerned about it. Furthermore, they also found that females under the age of 30 were the most represented group that did not see any major health risks of reusing greywater.

3.6 Water quality requirements

pH, turbidity, and conductivity are three important parameters to monitor in a water supply system (WHO, 2022). Even though these parameters usually are not harmful on their own, they can indicate the presence of other pollutants that are damaging to humans or the environment.

3.6.1 pH

One parameter that is extremely important to keep track of in water is the pH, even though this usually does not pose a threat to human consumption. The pH of water can affect the efficiency of treatment processes, and if chlorine is used, a pH lower than 8 is preferred (WHO, 2007). If water with a low pH is in contact with metals, it can cause corrosion on the surfaces. According to WHO (2007), the pH of drinking water mostly falls within the range of 6.5 to 8.5. They do, however, stress that there is no need to implement an exact guideline value for drinking water based on health risks. The United

Republic of Tanzania (2007) has on the other hand, proposed guidelines for drinking water in Tanzania and recommends that the pH is somewhere between 6.5 and 9.2.

It is important in agricultural areas to maintain the pH level in the soil to ensure a good environment for the crops to grow (Poyen et al., 2018). It is neither good to have a too acidic or too alkaline environment. A good interval is to keep the pH between 5.5 and 8 when growing vegetables and other crops. However, the most suitable pH depends on what types of crops are grown. Crops that are grown underground like potatoes and peanuts prefer acidic environment, while crops grown above ground like leek and cabbage prefer alkaline environment (Poyen et al., 2018). Since the pH of water affects the pH of the soil, it is important to track the pH in water used for irrigation. As different crops thrive in different environments, it is better to aim for a relatively neutral pH value in irrigation water (Malakar et al., 2019). Rainwater is naturally slightly acidic and usually has a pH of around 5.6 (EPA, 2025b). Acidic rain has an even lower pH, with pH values usually under 5. This is something that needs to be considered if rainwater is harvested and then intended to be used for purposes like irrigation.

3.6.2 Turbidity

Turbidity measures the clarity of a liquid sample, and is an important pollutant to test in water, as it can provide important information about the contamination level (WHO, 2017). Although turbidity itself is not harmful for human consumption, it can indicate a presence of other pollutants that are. It is the level of presence of these suspended particles that decides the turbidity of the water. These can, for example, be clay or organic matter, but also microbial or chemical contaminants. Two of the most common units to measure turbidity in is Formazin Nephelometric Units (FNU) or Nephelometric Turbidity Units (NTU), where the first is according to the ISO 7027 and the latter from USEPA Method 180.1 (Dogliotti et al., 2015; Ziegler, 2002). These two units are seen as being equal, however, as FNU is more commonly used in Europe, that is the unit that will be used in this thesis.

Events like storms or fires can increase the turbidity of surface water in a nearby area (WHO, 2017). The presence of forests or other vegetated areas is another influential factor, as leaves or other plant debris in water increases its turbidity. Turbidity is important to measure in water that is being stored, for example harvested rainwater, because if the turbidity increases, it can indicate a worsened water quality. In addition to indicating possible contamination of other pollutants, turbidity also has an aesthetic impact on the water as a turbidity of 4 FNU or higher is visible to the naked eye (WHO, 2017). This can influence a person’s willingness to consume or use high turbidity water. According to WHO (2017), the turbidity for drinking water should be kept at lower than 5 FNU, and ideally under 1 FNU. The Tanzanian guideline values for drinking water is set to between 5 and 25 FNU for turbidity (United Republic of Tanzania, 2007). Regarding irrigation purposes, turbidity should be kept as low as possible in water used for irrigation (Malakar et al., 2019).

3.6.3 Conductivity

Conductivity measures how well water can conduct electricity, and since salts and inorganic chemicals transport electricity well, a high conductivity indicates a presence of these (EPA, 2025a). The conductivity also increases with an increasing temperature of the water. WHO (2022) does not state any specific guidelines for the conductivity in drinking water, although they stress the importance of measuring it as a high conductivity can indicate pollution. While Tanzania does not provide any guidelines for conductivity in drinking water, it is still recommended to keep drinking water at a conductivity under 1500 µS/cm (Japan International Cooperation Agency, 2008). According to Zaman et al. (2018), the water used for irrigation should have a conductivity of at least 200 µS/cm to not disturb the salt contents in the soil. On the other hand, the conductivity should not be too high as this can lead to salinisation of the soil which can damage the crop productivity.

4 Methodology and materials

This chapter presents the methodology and materials used in this study to investigate the water quality, water management, and rainwater harvesting potential at Tumaini Open School. It describes the systematic approach taken to collect and analyse field data, including soil infiltration testing, water sampling, and water quality assessment. The chapter also explains the design and dimensioning of a rainwater harvesting system based on local rainfall and water demand estimations, as well as the evaluation of greywater reuse options. Ethical considerations related to working in the local community and environment are addressed to ensure responsible and respectful research practices. These elements provide the practical framework necessary to explore and address the water-related challenges of by the school.

4.1 Literature study

To gather relevant background information about water scarcity, RWH, floodings, and greywater, a literature study was conducted in the initial stage of this study. The databases Scopus and Google Scholar were used to find information about these topics, both from a general perspective, but also more specific information related to Africa and Tanzania. Some of the keywords that were used in the search strings to find references included *"Floodings", "Water scarcity", "Rainwater harvesting", "Greywater", "Topography",* and *"Tanzania"*. The information used was mostly from papers published in journals or books, but grey literature was also utilised. Grey literature is information that is not published in scientific journals and can for example be from governmental organisations, nongovernmental organisations, authorities, or businesses (Gul et al., 2021). This information is not necessarily less trustworthy than white literature such as books and journals, but it is not considered scientific due to potentially being politically or commercially related. In fact, grey literature can even be more up to date compared to white literature and contain information that is not published in these (Gul et al., 2021).

The availability of more specific information, mostly about Tabora or Tumaini Open School, was almost non-existing through the databases Scopus and Google Scholar. Information about this was instead found through grey literature like the municipal webpage. However, other sources like the school's website and the authors own observations during the field study were also used. Thus, the literature used for information about Tabora, or the school generally tended to be of lower quality.

Once a relevant sample was found, the snowball method was used to gather more relevant samples by utilising the first sample (Naderifar et al., 2017). By applying the snowball method to the literature study, similar studies or references of relevant articles were investigated to see if any suitable articles of the same topic could be found. Furthermore, the literature study was performed as an iterative process. Although a large part of the literature study was performed prior to the field study, the information was updated upon arriving at the site and performing the field study.

4.2 Land survey

The first part of the field study consisted of a land survey where the school's plot and its surrounding areas were analysed. A topographic study was performed to collect elevation data and model floodings in the area caused by heavy rain events. Furthermore, measurements of soil infiltration were made to better understand the behavioural patterns of stormwater from rainfall in the area.

4.2.1 Measurements of soil properties

The infiltration of the soil in the case study area was measured to estimate the runoff coefficient of the surface, which was needed as an input for the flood simulations performed in Scalgo Live. It was also measured to get a general understanding of how rainwater flows in the area; if it infiltrates quickly or if it mostly moves on top of the soil.

The method used in this field study was the DRI constant head test according to the standard of ASTM International (2018), but with some modification due to limited resources. This method was chosen as previous studies have proven it to be a suitable and relatively accurate test method to measure soil infiltration in field (Gregory et al., 2005; Johnson, 1963; Zhao et al., 2019). The materials used for the test was a bucket filled with tap water, a ruler, a stopwatch, two steel cylinders with a height of 20 cm and diameters of 30 and 60 cm respectively, as well as a plank and a stone to hammer down the cylinders into the soil.

The infiltration of the soil was measured in two places at the school area. The first infiltration test was performed on the 3rd of April, just outside the living area for volunteers and teachers, around 10 m from the area where a large puddle usually forms after heavy rainfalls. The soil there was very compact and classified as loamy sand. When the test was performed, there had not been any rainfall for 6 days, and the weather conditions during testing were sunny, around 29°C, and a light breeze. When performing the experiment, the cylinders were placed in an area covered by shade to minimise water evaporation. The second test was performed on the 15th of April in an area outside the school building. The soil there had similar properties as in the first testing location but was less coarse and therefore classified as silty sand. This location was more prone to sun exposure when performing the experiment, but the cylinders filled with water were constantly kept in the shade. During the time of testing, the sky was clear and the temperature around 28°C. It was slightly windy, and the soil was quite dry as there had not been any rain at the site for 7 days.

In the test locations, the two cylinders were first pushed 4 cm into the soil to ensure there were no gaps where water could leak. It was important to make sure that both cylinders were inserted into the same depth, to limit water leakage (Johnson, 1963). Before the infiltration test started, the soil was pre-soaked by filling both rings with water to a 100 mm level before leaving all the water to infiltrate. This was done to simulate saturated conditions for the soil.

Once the soil was pre-soaked, the infiltration test started. Both cylinders were filled with water, and once again, it was important to make sure they were filled to the same level. These water levels were then kept at a constant level of 100 mm by adding more water over time manually by pouring from a flask. When adding water to the cylinders, the water was poured over a hand, to minimise splashing that could damage the soil structure within the rings. After certain time frames, each between 5 and 60 minutes, the water level in the inner ring was noted, as well as the time elapsed since the water level last was at 100 mm. The difference in the water level is equivalent to the volume of water that has infiltrated into the soil (ASTM International, 2018). Water was then added to fill the water level up to 100 mm again, and after a certain time the water level was measured again, before it once again was filled to 100 mm. Figure 4.1 shows what the cylinders look like once they were filled. Measurements of the water level was carried out frequently in the beginning, and the time intervals between each measurement then increased as time went by. This process was repeated until a steady state was reached, meaning that the variation in water level was low. The water level differences for each time interval were divided by the time intervals to retrieve the infiltration rates. A final infiltration rate was then calculated as an average of these.

Figure 4.1: Picture showing how the experiment was executed.

Once the infiltration rate was calculated, it was used to estimate the runoff coefficient of the soil. The runoff coefficient is a dimensionless factor that represents the portion of the rainwater that becomes surface runoff. It is an important input value for hydrological modeling, including flood simulations in tools such as Scalgo Live. To determine the runoff coefficient, the first step was to classify the soil type based on the measured infiltration rate. The classification followed guidelines from the Minnesota Stormwater Manual, which link infiltration capacity to general soil types (Minnesota Pollution Control Agency, 2023). The measured infiltration rate at each test site was compared to Table 4.1 to assign a corresponding soil type. This classification was essential for determining the next step, which was the runoff coefficient. Field observations were used to estimate the surface gradient at each test location. Based on the classified soil type and the observed slope, the runoff coefficient was once again retrieved from the guidelines for assigning runoff coefficients from the Minnesota Stormwater Manual in Table 4.2 (Minnesota Pollution Control Agency, 2025).

Table 4.1: Infiltration rates of different soil types (Minnesota Pollution Control Agency, 2023).

Soil Group	**Soil Texture**	**Infiltration Rate (mm/hr)**
A	Gravel, Sandy Gravel	41.4
A	Sand, Loamy Sand, Sandy Loam	20.3
B	Silty Sands	11.4
B	Loam, Silt Loam	7.6
C	Sandy Clay Loam, Silts	5.1
D	Clay Loam, Silty Clay, Clay	1.5

Table 4.2: Runoff coefficients for different soil types and slopes (Minnesota Pollution Control Agency, 2025).

Soil Group	0-2% Slope	2-6% Slope	>6% Slope
A	0.08	0.13	0.16
B	0.11	0.15	0.21
C	0.14	0.19	0.26
D	0.18	0.23	0.31

The coefficient was then applied as an input parameter in hydrological simulations in Scalgo Live to represent the portion of rainfall expected to run off the surface rather than infiltrate into the soil. The accuracy of this approach relies on appropriate field classification and on using well-documented hydrological tables.

4.2.2 Topographic study

A topographic study of the area was conducted to gather information of the elevation differences around the school to map out how rainwater flows and where it accumulates. The methods chosen for the topographic study involved collecting data with a handheld GPS and then analysing it in QGIS and Scalgo Live. The choice of method was based on the size and the characterisation of the case study area, the level of accuracy needed, the available budget, and the time available for conducting the land survey. Elevation data could be retrieved online as it is available as open-source data. However, the resolution for global data is only around 30 m, and therefore not very precise. Collected data was therefore merged with open-source data to improve the resolution and increase the accuracy.

The device used to conduct the topographic study was a handheld GPS unit named Garmin GPSMAP 65s, which has an accuracy of being within 3,65 m (Garmin, 2020). The device uses both multi-band and multi-GNSS technology. This means it can track several signals from a single satellite, as well as connect to several satellite systems at the same time, leading to an increase in accuracy (Yang et al., 2019). This includes signals from the satellite systems GPS, Galileo, and GLONASS. Before starting any collection of data, the compass on the device was calibrated to ensure it worked correctly. This was recommended to do after experiencing large changes in temperature or travelling long distances (Garmin, 2020).

To ensure a stable satellite connection, the handheld GPS was turned on a few minutes before gathering the data. No data collection was performed before the highest available GNSS-accuracy was established, which could be seen by looking at the satellite coverage in the Garmin handheld GPS. After the device had stabilised, tracks containing information on geographical positioning were created. A track is a sequence of recorded points, where every point contains information of horizontal and vertical coordinates (Garmin, 2020). When staring a new track, the device was held while moving around and along the land belonging to the school, but also in surrounding areas. During surveying, the GPS was always held at approximately one m over the ground. More dense data was gathered within the school's land area because the priority was to get more accurate data there. The areas outside of the school area was surveyed only by walking around on walkable roads and paths, resulting in less dense data collection in these locations. To improve the accuracy of the measured data, multiple tracks in the same areas were recorded at different times of the day during different days. The elevation data was gathered between the 21st of February and the 20th of April. In total, 24 tracks were collected, which resulted in elevation data gathered in 4596 points. More specific information regarding the date, time, weather conditions and areas of data collection are shown in Table A.1 and Figure A.1 in Appendix A.

4.2.3 Measurement of the school area

The handheld GPS was also used to measure the size of the school's land area. Before data collection, the satellite connection was controlled to ensure that it was sufficient, and the GNSS-service accuracy was recorded. In the Garmin device, "Area Calculation" was enabled, and a walk along the borders of the school's plot was conducted. When all the land area had been covered, the area was immediately calculated by the handheld GPS and noted. During the walk, the handheld GPS also recorded a track along the school's land area limits. This recording was later used in the topographic study where the elevation of the school area and its surroundings were examined.

This procedure of recording area of the school's plot was repeated two more times during different days and different times of the day to establish a more accurate result. Recordings of the time, date, and weather conditions when sampling the school's land area are presented in Table A.2 in Appendix A. These measures include the land area that does not belong to the school but is surrounded by land belonging to the school. The GPS files of the land area were imported as vector datasets into QGIS to correct the land area of the school by removing a piece of land within the outer boundaries of the school but does not belong to the school. An average of the corrected land area was then calculated based on the three land area measurements.

4.2.4 Analysis of collected GPS data

The GPS data generated from the topographic study was uploaded to QGIS where it was converted from GPX files to GeoPackage formats to support Scalgo Live. The DEM for the Tabora region was downloaded. It had a resolution of 30 m and used the coordinate system EPSG:3857. The collected GPS data was then transported into vector layers, which were used to enhance the existing DEM of Tabora and its nearby areas. All the data from the tracks was merged into one layer in QGIS. The merged GPS data layer was then reprojected into the EPSG:3857 coordinate system to make it compatible with the original DEM. The reprojected GPS data was interpolated with a 5 m resolution using TIN interpolation. The chosen attribute was elevation, which meant that QGIS estimated the elevation in between the data points. The 5 m resolution was chosen since it was the highest possible accuracy guaranteed by the GPS data. The TIN interpolation utilised the collected points containing elevation information to estimate the elevation in areas around the points. This resulted in an interpolated layer that covered significantly more of the land areas that were not covered by the GPS data points. The merging of the interpolated layer and the original Tabora DEM layer using the Raster Calculator in QGIS helped reducing the risk of relying too much on estimated data in between actual measurements. The merge was done with a weight ratio of 40% TIN interpolated GPS data and 60% pre-existing Tabora DEM. The reason for the slightly lower GPS weight was due to potential inaccuracies of the GPS data collection. The result of each set of the two merged layers was a final interpolated DEM which was then exported as a raster file in a Scalgo Live compatible format, in this case, GeoTIFF.

In Scalgo Live, the final interpolated DEM was uploaded as a custom Workspace, which allowed for a more detailed topographic analysis than what was possible with the original 30 m resolution model. Using the hydrological tools available in Scalgo Live, simulations were performed to model how water would flow and where it would accumulate during heavy rainfall events. A specific rain event with 80 mm rain was selected for the flood simulation. This volume was chosen because it represents a realistic scenario based on recent weather observations during fieldwork. The simulation generated flood maps which visualised the areas that were most prone to surface water accumulation. These visualisations made it possible to pinpoint parts of the school that are particularly vulnerable to flooding. In addition to the flooded areas, the Flow Accumulation and Depression-Free Flow Accumulation tools in Scalgo Live were also used to analyse the water movement across the terrain. Flow Accumulation helped in identifying how water collects as it flows across the surface between depressions. Areas where multiple flow paths converge were treated as particularly critical during the analysis. Depression-Free Flow Accumulation was used to model how water would behave if natural depressions were filled or bypassed. This gave insight into worst-case scenarios or areas that might benefit most from drainage interventions. The analyses were not only used to identify flood-prone zones, but also to provide information used as a basis for flood mitigation measures. The integration of GPS-enhanced terrain data into Scalgo Live provided a hydrological assessment that was grounded in both collected field data and simulations. This methodology enabled a more detailed understanding of floodings affecting the school.

4.2.5 Field observations of floodings

Most of the larger rain events with impact on the land occurred during night when measurements or observations of the surrounding environment were not possible. For these rain activities, the total rain volumes acquired during the nights were measured instead. The rainwater during night was collected by using a conical flask and a funnel. The flask had a maximum measurement of 500 ml, and the funnel had a diameter of 90 mm. When calculating the total rain volume that was collected overnight, the water volume was converted from ml to mm^3, before it was divided by the circular area of the funnel. No rain intensity was calculated as it was impossible to know for how long the rain events occurred during the night. When large volumes of rain had been collected during the night, field observations around the school area were made in the early mornings. The locations where consequences from the rainfall could be seen were noted and then investigated further to see how they changed during the day. When rain events occurred during the day, the area was investigated during the rainfall.

4.3 Water quality assessment

As the second part of the field study, samples of water from different sources around the school were collected and then analysed to test the water quality to get an understanding of the level of pollution.

4.3.1 Sampling of water

The sampling of water was conducted for three different types of water sources: rainwater, municipal water, and water from a shallow well. The sampling IDs, date, and location of samples are presented in Table 4.3. The samples were collected in disposable plastic test tubes and in total, 36 samples were collected. Three samples were collected for each sampling point to get a more reliable result when analysing. The rainwater samples were collected on the 7th of April between 07.00 and 07.30 in the morning. Three samples of around 40 ml were collected from one point before moving on and sampling in the next point. The rain activity for which the rainwater samples were collected had been going on during the whole night, and therefore no first flush of rainwater flowing from the roofs was sampled. The sampling of the non-rainwater was carried out on the 3rd and 8th of April. Again, three samples of around 40 ml were collected from each sampling point. The rainwater and non-rainwater samples were sampled on different days due to the limited number of available test tubes. The test tubes were thoroughly rinsed twice with distilled water before reusing them for collecting new samples.

Table 4.3: Information of collected water samples. Includes time of sampling and a short description of what type of water is sampled and where.

Sampling ID	Date	Description
1, 2, 3	2025-04-07	Water accumulating on ground, sampled outside volunteer’s house
4, 5, 6	2025-04-07	Rainwater directly from sky, sampled outside volunteer’s house
7, 8, 9	2025-04-07	Rainwater from roof: Volunteer’s house (west side)
10, 11, 12	2025-04-07	Rainwater from roof: Teacher’s house (east side)
13, 14, 15	2025-04-07	Rainwater from roof: School building (west side)
16, 17, 18	2025-04-07	Rainwater from roof: School building (east side)
19, 20, 21	2025-04-07	Rainwater from roof: Student’s dormitory (east side)
22, 23, 24	2025-04-07	Rainwater from roof: Student’s dining house (north side)
25, 26, 27	2025-04-03	Municipal water from plastic tank outside volunteer’s house
28, 29, 30	2025-04-03	Municipal water from tap in volunteers house
31, 32, 33	2025-04-03	Water from shallow well
34, 35, 36	2025-04-08	Greywater from laundry done by hand. Contains soap and washing detergent

All the rainwater samples were collected during the same rain event. This was done to limit any possible differences between the samples, since both the rain intensity and the days between rainfall affect the water quality (Yaziz et al., 1989). Long periods without rain lead to more pollutants in the air depositing on the roofs to pollute the rainwater harvested from the roofs. The intensity of the rain, especially in the beginning of a rain event, decides how quickly the roofs are “cleaned” from contaminants on the roof. The higher the intensity of the rain, the quicker the roofs are cleaned from the first flush (Yaziz et al., 1989). As mentioned, no samples of the first flush were collected in this study and this was planned from the beginning. One of the reasons for this was because of logistic reasons, as it would be difficult to manually collect representative first flush samples from multiple roofs in spread out locations at the same time. It was also difficult to distinguish the first flush from the rest of the rainfall as most rain events started gradually before increasing in intensity. Furthermore, the field study was conducted during the rainy season when rain events occurred almost daily. Because of this, particles stuck to the roofs were disposed of regularly and the difference between first flush samples and the rainwater collected afterwards was expected to be very small.

4.3.2 Measurement of rain intensity

Rain intensity is usually measured in millimeters per hour and WMO (2008) classifies rain intensity (i) into light (i < 2,5 mm/h), moderate (2,5 ≤ i < 10 mm/h), heavy (10 ≤ i < 50 mm/h), and violent (i ≥ 50 mm/h). The most common method used to test the intensity of rain is to use a rain gauge, usually in the form of a cylinder pipe, and then measure the volume that is filled in a certain time span (WMO, 2008). This method was therefore adapted when measuring the rain intensity at the site. During the rain event when samples were collected, a conical flask with a funnel on top of it was placed outside to collect water during a set time. The same material and methods described in Section 4.2.5 were used to calculate the total volume acquired during the rainfall. This volume was then divided by the time it took to collect the water to retrieve a rain intensity in the unit mm/h.

4.3.3 Motivation for sampling points

When choosing which roofs to sample rainwater from, all the roofs that were large enough to possibly be utilised for RWH were analysed. These roofs could be divided into three areas that each contained multiple roofs. The roofs in each area were located close to each other so the water retrieved from these roofs could be led to the same tank. The first area was the school area, and since this beforehand was believed to be the most suitable placement for a RWH system, sampling of this roof was prioritised. Therefore, samples were taken from both the east and the west facing roof surfaces on the school building's roof. The second area was the residential area for the students where both the dormitory and the dining hall roofs were seen as suitable surfaces. Here, samples were taken from both buildings as they had different shapes and slopes on their roofs, which potentially could imply differences in water quality. The third area that was identified to have a potential of RWH was the residential area for volunteers and teachers. Here, samples were collected from both the volunteers' and teachers' houses, but not from the small kitchen building right next to them. The reason for this was because it was the smallest of the buildings, and the almost flat roof on the building complicated the sampling process. Instead, the two samples from the volunteers' and teachers' houses were seen as enough as they were expected to show similar results to the small kitchen building in the analysis. Furthermore, other small sheds or buildings were also excluded from the sampling process. This was because they were not seen as roofs suitable for a RWH system as they were older than the rest of the roofs at the site and had visible rust spots.

The reason for collecting rainwater directly from the sky was to compare it to the samples of rainwater collected from roof areas, to see how big of an impact the roofing materials and possible contaminations on the roof had. The collection of rainwater accumulated on the ground was also sampled for comparative reasons.

4.3.4 Analysis of water quality

The parameters that were analysed for the water samples were pH, turbidity, and conductivity. Physiochemical parameters were analysed because rainwater collected from roofs react physiochemically with the roof materials (Lee et al., 2012). Since the analysis was carried out outside of a laboratory, the methods were adapted and simplified to enable traveling with them and using them in field. The methods used were therefore expected to result in less accurate results than if the samples were analysed in a laboratory environment. Since no chemicals or other toxic substances were used during the analysis, no extra protective gear like safety glasses, safety gloves, or protective clothing had to be used. The collected samples also originated from water sources believed to be rather clean. The samples containing greywater were, however, treated carefully as they were believed to be the most polluted. When handling these samples, safety gloves were used.

The pH was measured by using MQuant pH-indicator strips by the brand Supelco. The strips can be used to test the pH of a solution in the range of pH 0-14, with the accuracy of 1 pH unit (Merck, n.d.). A strip was inserted into the water in the sample container for around a minute which caused it to change colour in four reaction zones on the strip. The colours of these zones were then compared to the enclosed comparative scale to determine the pH of the water. The process was repeated for the rest of the samples by using a new strip for each sample respectively. Although the pH-indicator strip is a simple method, and despite that there are more accurate methods available like a pH-meter, Duggan et al. (2008) found a high correlation between the results using a pH-indicator strip and a pH-meter, and that the strips therefore could be used when the accuracy of the result does not need to be more than 1 pH unit. The method is suitable for this study as the reason for testing the pH in the water was mostly to get an indication of the quality, which meant that more specific measurements were therefore not needed.

Turbidity was tested by using a handheld turbidimeter named turb 430 IR. The turbidimeter measured turbidity in the range of 0,01 to 1100 FNU/NTU by using infrared lighting (WTW, 2022). Before the analysis of samples, three cells of standard solutions with a known turbidity of 1000, 10, and 0,02 NTU were used to calibrate the device. The calibration program in the turbidimeter was started and the instructions that appeared on the screen were followed. The cells of standard solution were wiped clean and inserted into the cell shaft of the turbidimeter one by one to perform the calibration. Furthermore, air bubbles in the samples were avoided as these can distort the light and lead to incorrect measurements (WTW, 2022). After that, the sampled water was tested. The samples were first shaken, before adding approximately 20 ml of the first sample to the test cell. The cell was then put in the cell shaft and the sample was analysed. The cell was rinsed twice with approximately 20 ml of distilled water before it was filled with the next sample. The process was repeated until all samples had been analysed.

For the conductivity analysis, a VWR HCO 304 conductivity-meter was used. The conductivity-meter consists of a 2-point measuring cell that measures parameters in a solution (VWR International, 2019). It measures conductivity within the span 0-200 mS/cm, and with an accuracy of ±0,5% of the measured value. Apart from measuring conductivity, the conductivity-meter also measures temperature, total dissolved solids, and salinity. The two latter were, however, not tested because they are similar to and can be derived from conductivity. Before using the conductivity-meter, the electrode was washed with distilled water. The conductivity and temperature of the samples were then measured by inserting the electrode into the container filled with the first sample. After a few seconds, the values for the conductivity and temperature were noted. The electrode was then rinsed with distilled water again before testing the next sample. This process was repeated until all samples had been analysed. The conductivity and the temperature were the last parameters that was analysed for the water samples. This was due to the risk of cross contamination of the samples, because the samples were tested by inserting the electrode into the original sample containers.

4.4 Water management

The third part of this study focused on the water management at the school. A daily water usage for the students and staff living at the school was investigated, which was used for the dimensioning of a rainwater harvest system. Furthermore, greywater usage was investigated to find a suitable solution for reusing it.

4.4.1 Estimations of current daily water usage at the school

The water demand, both current and for the future, of Tumaini Open School is difficult to estimate since the school is constantly expanding and performing construction work which results in a higher water usage. The expansion also leads to a constantly increasing number of students at the school, which furthers increases the demand for water at the school. Data of the water usage at the school is presented in Table 2.1 in Section 2.4. However, this is only data from three months during the rainy season, which means the usage cannot fully be seen as representative for an average water demand. Estimations were made to try and calculate how much each person uses, and to calculate a future water demand. This is valuable information for deciding the dimension of a RWH system. The daily water usage estimations were based on both the available data from the school, but also multiple reference values and rural water consumption patterns, essential personal water needs, as well as requirements for communal sanitation, cleaning and landscaping.

The United Nations (n.d.) recommend a daily water consumption of 50 lpcd to meet basic needs, which includes drinking, hygiene, and domestic use. However, the actual water consumption varies depending on local infrastructure and access to water. According to Gleick (1996), the water consumption in rural areas ranges between 20 and 40 lpcd. The students and staff on the school grounds have access to running water in close vicinity to their accommodations, thus, the school environment upholds a relatively high standard compared to other rural areas. Therefore, it is reasonable to assume that the water consumption at the site is at least 30 lpcd. In addition to personal consumption, UNICEF (2020) highlights that communal sanitation, cleaning in shared spaces, for example a school, require an additional 5 to 10 lpcd. Since Tumaini Open School has a large school area with several shared buildings and living areas, an additional water usage closer to 10 lpcd is most likely appropriate. Furthermore, WHO specifies that 20 lpcd is necessary for essential water uses such as drinking, cooking, food hygiene, handwashing, and face washing (Howard et al., 2020). Based on this data, along with field observations of water usage at the site, the total daily water consumption at Tumaini Open School is expected to fall within the range of 40 to 50 lpcd. This estimate accounts for the relatively high rural standard of living, the communal sanitation and irrigation needs, and personal water requirements. The estimations were done separately for the students, teachers and volunteers, as their water consumption was believed to be different.

Apart from personal and communal consumption, additional water is required daily for irrigation and construction work. The estimated monthly water use for each person living at the school was subtracted from the acquired monthly water consumption data at the school, which is shown in Table 2.1 in Section 2.4. The excess water was assumed to be the water used for irrigation and construction work.

4.4.2 Design of a rainwater harvesting system

The RWH system considered most suitable for the Tumaini Open School was collecting rainwater from roofs and transporting it into a tank to store for later usage. A simplified Excel-based model was used to determine a suitable storage tank size for the RWH system. The required input data included runoff area, runoff coefficient, storage tank volume, daily rainfall, daily mean and maximum temperature, and the daily water demand. The calculations included potential daily water collection, daily water balance in the tank, evaporation losses, and tank performance evaluation. The amount of rainwater collected each day was calculated from the rainfall data, roof catchment area, and runoff coefficient. The rainfall and roof areas were used to calculate how much water could be harvested each day, while the runoff coefficient was applied to account for losses due to evaporation and inefficiencies in the collection system. Evaporation losses were also estimated due to the daily temperatures. The daily water balance was tracked by comparing the incoming rainwater with the school's daily consumption.

The water demand at the school was estimated based on literature as well as the recorded water usage data from the 11th of January to the 11th of April. The rainfall data was obtained from the CHIRPS Data Portal (Climate Hazards Center, 2025), which provides precipitation data at a 5 km resolution. This was the most detailed source available for the case study area. The geographical coordinates of Tumaini Open School were used to extract the rainfall data from the nearest weather station. The dataset used for the study covered the period from 2000 to 2024 and it was converted into an Excel format for further calculations. Temperature data for the same period was retrieved from an open-source database based on WMO records (Meteomanz, 2024). Since detailed daily temperature data was not available, monthly average temperature data was used for the days within each corresponding month. This was considered sufficient as the temperatures are considered relatively stable with low daily variations.

The roof areas that could potentially be used as collection surfaces in a RWH system were measured to a one decimal precision using a 100 m measuring tape. Area measurements were taken for the roofs on the school buildings, the dormitory and the dining hall for the students, the accommodation for the teachers, the accommodation for the volunteers, as well as the small kitchen building in the living area for teachers and volunteers. The area of the small kitchen building was included even though no water from its roof was sampled.

The tank size input value was variated in the Excel to assess the coverage rate of the water demand throughout a year. The model identified how the periods of water excess and shortages affected the efficiency of the tank, which helped determine the most effective tank size for the school. The final recommendation on tank capacity was based on balancing water availability, storage efficiency, water demand coverage rate, and practical implementation.

The RWH system includes collection of rainwater from sloped roofs and transportation through gutters and downpipes into the storage tank. The dimensioning of these were done using an Excel model supported by flow capacity charts and manufacturer specifications for typical PVC and stainless-steel gutters and pipes. The model estimated the required dimensions based on the peak flow rate of rainwater during short duration, high intensity rains. Similarly to the dimensioning of the tank, the input data included total roof area, a chosen runoff coefficient, peak rainfall intensity, and slope assumptions for gutters and pipes. The calculations were used to determine the volume of rainwater flowing off the roof during peak events and the minimum dimensions required to safely transport this volume without overflow.

For the calculations, a runoff coefficient of 0.9 was selected based on stainless steel roof sheets and the minimal losses due to infiltration. The peak rainfall intensity used for the dimensioning of gutters was set at 20 mm/hr, which was based on field measurements, precipitation data from CHIRPS Data Portal (Climate Hazards Center, 2025), and the fact that this intensity corresponds to WMO’s classification of heavy rainfall (WMO, 2008). These values were used to estimate the peak runoff from the roof, using the rational method in Equation 3.1. Each gutter was assumed to be sloped at a minimum gradient of 1% in accordance with requirements for gravity-based conveyance systems. Gutter sizes were calculated using SMACNA’s Downspout & Gutter Sizing Calculator (Sheet Metal and Air Conditioning Contractors' National Association, n.d.). The gutter dimensions were then selected from standard commercially available profiles based on their maximum flow capacity under the assumed slope and rainfall conditions (Guttercrest, n.d.). The dimensions for the downpipes and connecting pipes were similarly selected by comparing the calculated peak flow to common pipe sizes and their estimated capacity. These dimensions were selected based on a pipe design guide (Metal Gutter Manufacturers Association [MGMA], 2012). A model of the proposed RWH design including the school building, the water storage tank and the gutters and pipes that directs the rainwater was then produced in Revit 2025.

4.4.3 Greywater reuse

The main greywater sources at the school were identified as hygiene, laundry, and dish washing. Although showering was estimated to contribute to the largest greywater production when looking at the consumption in lpcd, handwashing of clothes was generally the activity that generated the most amount of greywater at the same time. This was therefore the water that was prioritised to reuse. Furthermore, as water from laundry was gathered in buckets, and not as spread out as water generated from other sources, it was also seen as the easiest water to gather for treatment. Many previous studies that investigate the public acceptance of greywater reuse show that for purposes that do not require any direct contact with humans, acceptance is higher. The reuse purposes prioritised in this study were therefore irrigation and construction work. The local conditions and resources available at the site were important to consider when designing a suitable solution for greywater management. The designs of the proposed treatment systems were based on previous studies where similar solutions had been implemented.

To get an understanding of the quality of the greywater, the water from the washing of clothes was sampled and analysed for pH, conductivity, and turbidity. The reason for only sampling water from clothes washing was partly because the reuse of this water was prioritised, but mostly to limit the risk for contact with greywater as it can be contaminated and potentially spread diseases. Water from washing of clothes was believed to contain less harmful bacteria than water from showering or washing of dishes. Furthermore, only water from the authors own clothes washing was sampled and analysed to take precautionary measures.

4.5 Ethical aspects

Several ethical aspects were considered when conducting the study. As this master thesis was partly conducted in a rural area in Tanzania, many considerations to the local environment were made. When performing the field work, the disruption of the environment was minimised as much as possible. The soil infiltration test was performed with no digging, excavation, or other lasting disturbances of the soil. Furthermore, the disturbance for nearby residents was limited when collecting GPS data in the area as living and cultivation areas belonging to the neighbours were not entered without approval. Instead, data was mostly collected by walking on public roads and open spaces.

Another ethical aspect that was considered was the local customs of Tanzania and Tumaini Open School. First, it was important to act and dress appropriately. The way of working with the field work was also adapted to the local working methods. Everyone at Tumaini Open School were aware of the project, and the representatives at the school that contributed with valuable information knew that the information might be used in the report. Furthermore, no pictures where the students or the staff at the school were visible were used in the report. Permission was asked for before photographing any buildings or other areas at the school.

5 Results and discussion

This chapter presents a detailed analysis of the field study findings, focusing on water management challenges at Tumaini Open School. The chapter proposes practical and context-appropriate solutions including rainwater harvesting, flood mitigation measures, and greywater treatment options. It also critically discusses the feasibility, benefits, and limitations of these solutions in relation to the local environment, social acceptance, and economic factors. Finally, the chapter discusses the methodologies, limitations and sources of errors in the study, as well as areas for future research to support sustainable water management at the school.

5.1 Estimated water demand at the school

Based on data in the literature, and observations from the field, a final daily consumption of 45 lpcd was estimated for the students at the school. For staff and volunteers, a slightly higher consumption estimate was used, based on the recorded consumption in their living quarters. The teachers were estimated to consume 50% more water than the students, equalling 67,5 lpcd. The daily water consumption for volunteers was estimated to be twice as much as the students, equivalent to 90 lpcd. One reason for this was that the volunteer's accommodation was equipped with more water demanding solutions for their showers and toilets compared to the rest. The teachers and volunteers were also expected to use more water daily for cooking and washing dishes, as they had a more extensive use of utensils and appliances when cooking and eating compared to the students.

When subtracting the personal consumption from the total water consumption at the school, a monthly consumption of water for construction and irrigation was estimated to be between 8 275 L and 29 275 L. The more critical scenario of a monthly consumption of 29 275 L was chosen. This corresponds to an average of approximately 975 litres per day (lpd) allocated to construction and irrigation. The water demand for irrigation is not expected to either increase or decrease in the nearest future since there are no current plans on constructing new or demolishing old spaces for crop farming. Similarly, the water demand for construction work is also expected to stay at a similar level. The water demand for irrigation and construction work at the site is therefore assumed to be relatively constant even for the future. The estimated demand for irrigation and construction work is only based on water consumption data from the school during the rainy season, which especially influences the water demand for irrigation purposes. The estimations would be more reliable if water usage data was available for a longer period, at least for a whole year. However, based on observations of the water usage for different activities at the site, the estimated consumption for both personal use and irrigation and construction work were seen as reasonable.

5.2 Soil infiltration and runoff coefficient

The recordings of the full data from the infiltration test are shown in Table B.1 and Table B.2 in Appendix B. The final infiltration rates of the sites were calculated to be 27 mm/h for the first test site outside the teachers' and volunteers' house and 13 mm/h for the other test site by the school. By using the data provided in Table 4.1 and Table 4.2 in Section 4.2.1, the infiltration rates of the soils in the two test sites were converted into runoff coefficients. Site 1 was classified as soil group A which corresponds to sand, loamy sand, or sandy loam while site 2 aligns with soil group B which is specifically associated with silty sands or loam. The infiltration rate for the second site slightly exceeded the upper threshold for group B, but it was significantly lower than group A, making soil group B the most suitable classification after all. The slope of the test sites was determined to be slightly higher for the first site compared to the second test site. The resulting runoff coefficients from this information are shown in Table 5.1. With the runoff coefficient being 0.13 and 0.11 for the two different sites, a runoff coefficient of 0.12 was used as an input parameter in the Scalgo Live simulations.

Table 5.1: Runoff coefficient results from the infiltration rates, soil groups and slopes of the infiltration test sites.

Site	**Infiltration Rate**	**Soil Group**	**Slope**	**Runoff Coefficient**
Test Site 1	27 mm/hr	A	2-6%	0.13
Test Site 2	13 mm/hr	B	0-2%	0.11

The method used for measuring soil infiltration could be improved if there was access to a laboratory. The conversion from soil infiltration to classification of soil group to a final runoff coefficient could have led to conversion errors or biased decisioning. This is especially evident as the classification of a soil group for the second test site did not completely follow the provided spans and was instead based on what was considered reasonable. However, the method used for deciding the runoff coefficient of the soil was still considered better than only using an estimated reference value, which was the other option available considering the circumstances. The method increased the reliability of the input parameters and minimised the dependency on default or generalised soil assumptions, hence the approach contributed to a more accurate flood risk assessment and water flow mapping.

5.3 Land area of the school

Table 5.2 shows the size of the school's land area when measured by using a handheld GPS and then correcting the data in QGIS to account for the removal of a piece of land not belonging to the school. The measurements show that the total average school land area was measured to 3.40 ha. The size of the land area of the school was used when proposing a suitable flood mitigation measure for the site.

Table 5.2: Results of the land area measured with a handheld GPS and then corrected in QGIS. The average of both is also included.

Sample	**Land area measured with GPS [ha]**	**Corrected land area measured in QGIS [ha]**
1	3.47	3.37
2	3.64	3.42
3	3.35	3.40
Average	**3.49**	**3.40**

5.4 Flood management

This section presents the results from the flood risk assessment regarding both the hydrological modelling in Scalgo Live and the field observations. Based on the results, a suitable flood mitigation measure is proposed. The proposed solution and the methods used to obtain the results are also discussed.

5.4.1 Flood simulation in Scalgo Live

The DEM used in the flood simulations in Scalgo Live was significantly improved by the integration of the collected GPS data. The updated DEM offered a more detailed and accurate representation of the terrain, particularly in the flatter or gently sloping areas that were not well-defined in the original model. These subtle elevation changes are very important for accurately modelling how water accumulates and flows across the site. A comparison between the original and the updated DEM showed that the inclusion of GPS measurements improved the model's alignment with the actual topography observed at the site. Figure C.1 in Appendix C shows the unedited elevation model in comparison to the model with integrated GPS data.

A flood map that highlights the depressions and low-lying areas with risk of water accumulation during heavy rainfall was produced in Scalgo Live. These flood-prone areas are shown in light to medium blue colours in the simulation results presented in Figure 5.1. The flood-prone areas within the school compound were primarily located in the southern part of the school area, also known as the residential area. The most affected areas included the surroundings of the students' dormitory and dining hall, as well as the open area near the volunteers' and teachers' houses. These findings emphasise the importance of integrating surface water retention features within the school compound and ensuring that crucial infrastructure such as classrooms, toilets and other frequently used buildings are situated outside of these vulnerable zones. Proper site planning based on flood risk is essential to mitigate future water-related damage and enhance the school's resilience to heavy rainfall events. Another aspect to consider is the importance of drainage around buildings to avoid any water-related damages on them.

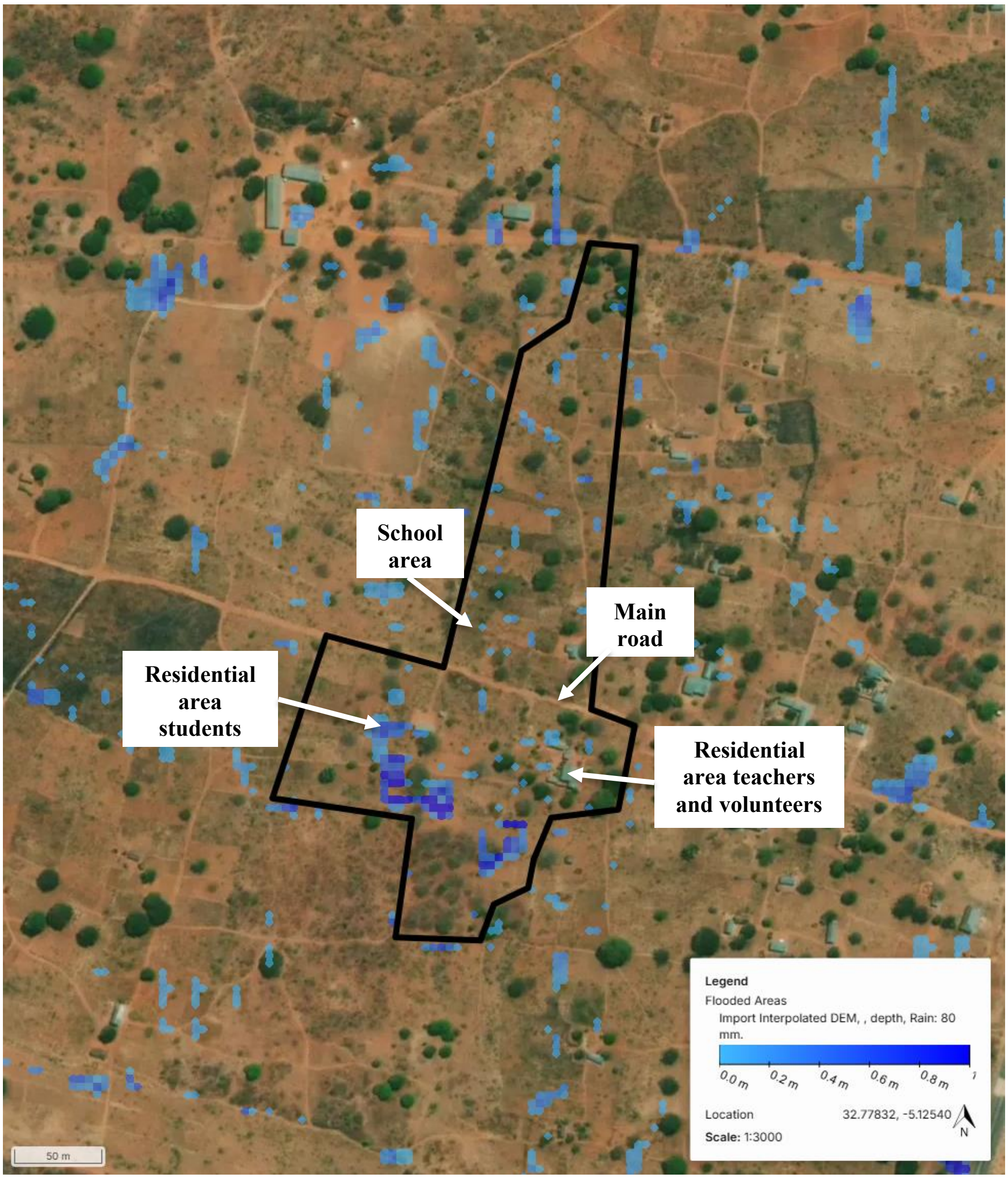

Figure 5.1: Flooded areas during an 80 mm simulated rainfall event at Tumaini Open School.

The flow accumulation tool in Scalgo Live provided valuable insights into the surface water runoff flows across the study area. These flow paths are illustrated as dark blue lines in Figure 5.2, where the line width corresponds to the volumes of accumulated flow. The most erosion-prone flow paths traverse the school grounds from west to east, specifically along the unpaved road that intersects the school area. This road connects the school to the main road and is therefore essential, especially for larger service and construction vehicles that need to easily access the school for delivering building material or emptying septic tanks. However, the current state of this road forces vehicles to take detours to reach the school area. The simulation results indicate that the main road concentrates a substantial portion of surface runoff and should therefore be prioritised in any future drainage system design. In addition to the main flow line, there are also several secondary flow lines that branch off from the main channel and create a water network that spans across large areas of the compound. These lines reveal zones of converging flows, which are particularly important to consider due to their high potential for soil erosion and structural wear.

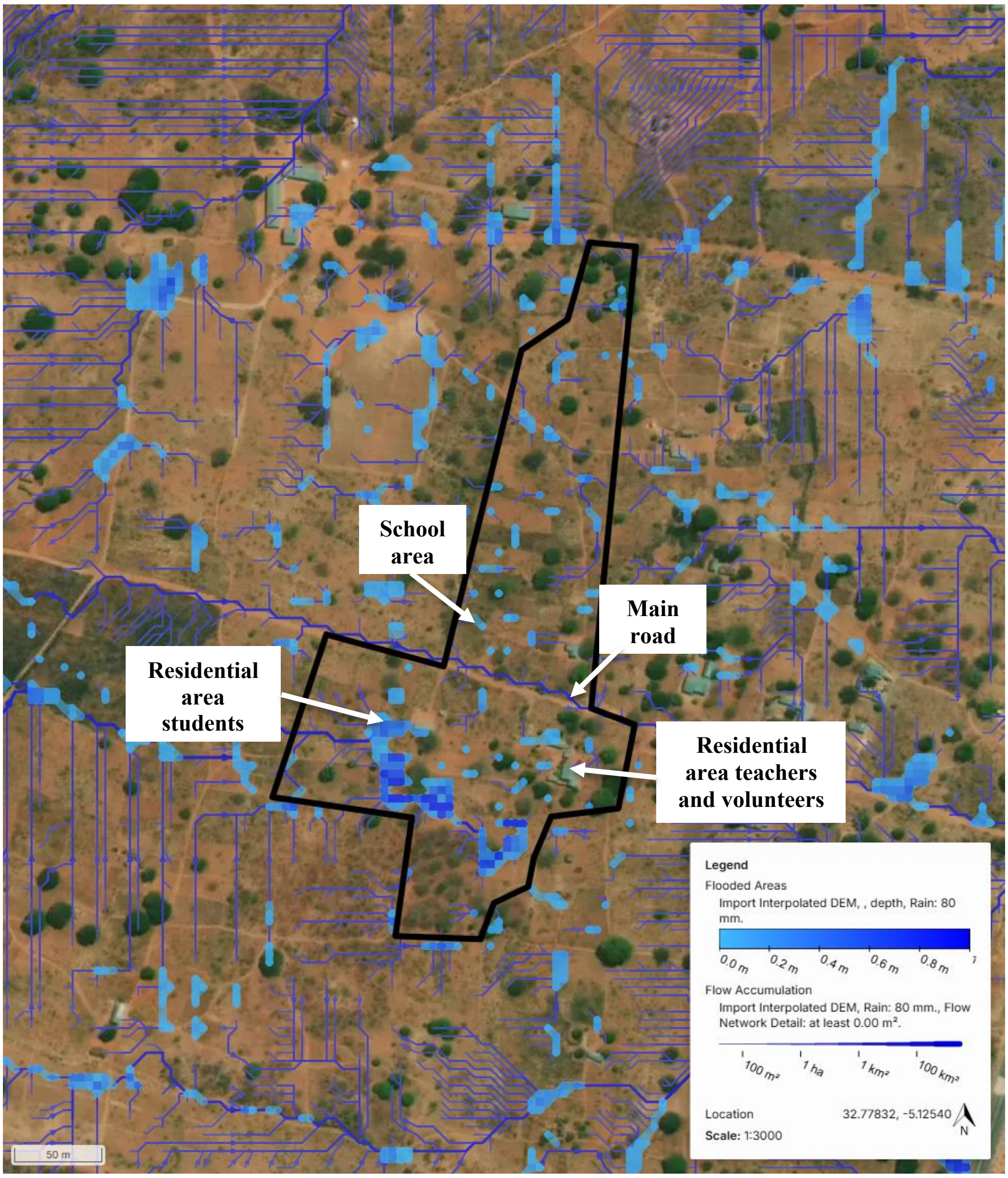

Figure 5.2: Flooded areas and water flow accumulations between water depressions during an 80 mm simulated rainfall event at Tumaini Open School.

Figure 5.3 shows the depression-free flow accumulation layer which presents a significantly denser and more connected network of surface runoff paths. This scenario assumes that all depressions are filled and models a worst-case runoff situation. Under these conditions, runoff spreads more extensively and converges more rapidly, particularly toward the southeast corner of the land area. This indicates an increased flood risk in this area during heavy rainfall events.

A notable feature in this scenario is the substantial water flow between the two residential areas in the southern part of the school. The simulation shows two prominent northwest-southeast water flow corridors that conveys and collects runoff from multiple upstream sources and increases the volume and surface flow rate on the unpaved road and the flow corridor between the inhabited areas. This has important implications for infrastructure and safety, and without proper intervention, these corridors could become erosion paths that could reduce accessibility and potentially cut off residential areas from the main road and the school, while posing risks to structures and sanitation facilities. Drainage interventions should therefore prioritise both northwest-southeast corridors.

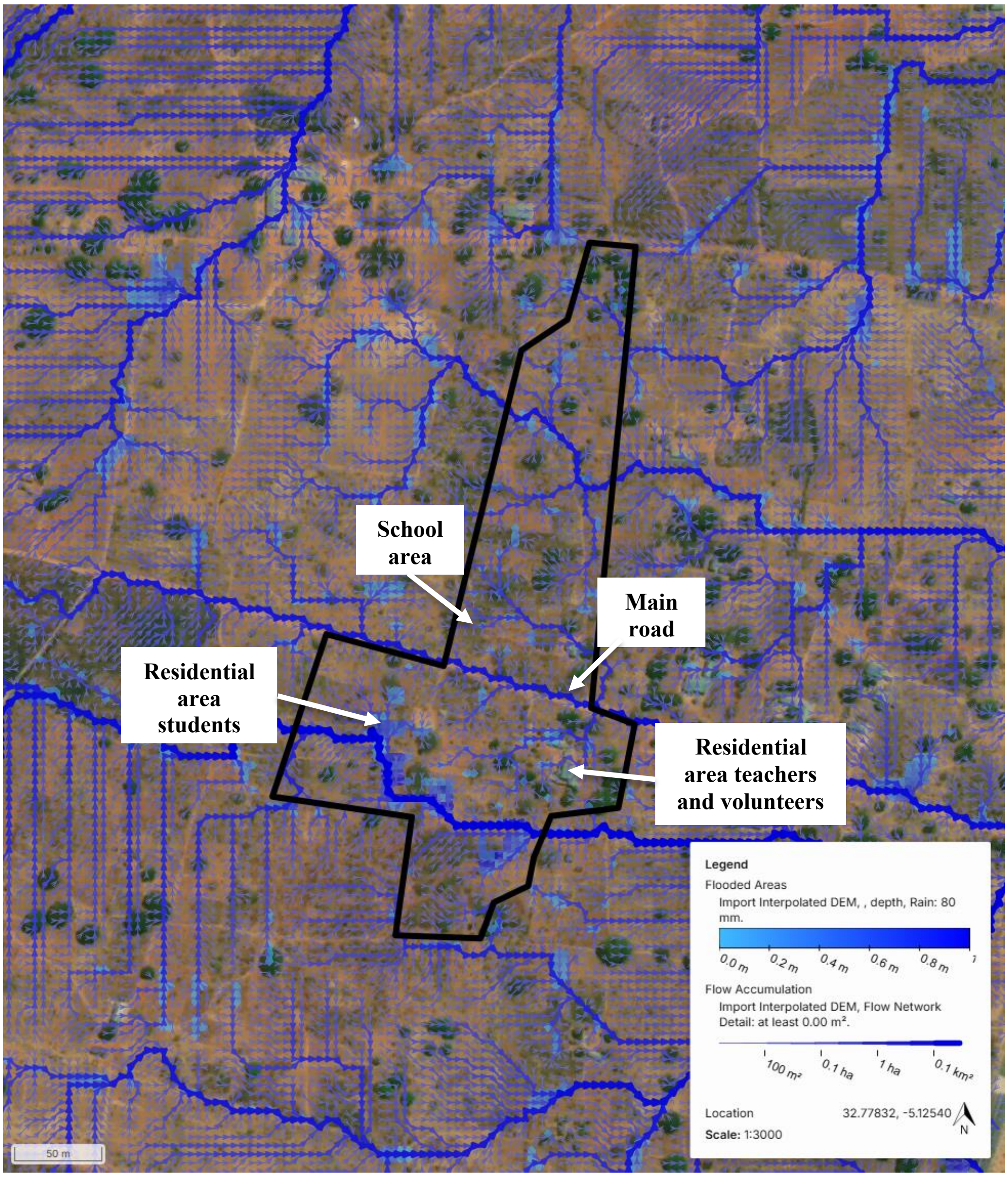

Figure 5.3: Flooded areas and depression free-flow water accumulations during an 80 mm simulated rainfall event at Tumaini Open School.

5.4.2 Field observations

Field observations were conducted both during and after rainfall events to verify and complement the Scalgo Live simulations. These observations helped provide a more nuanced understanding of how water behaves across the school grounds under different rain conditions. A detailed field observation protocol, which includes information regarding the rainfall volumes and their environmental impacts at the case study site, is provided in Table D.1 in Appendix D.

The field observations showed that the most evident flood-related problem at the site was soil erosion, particularly along the larger roads. Both the main road crossing the school area from west to east, as well as other larger internal roads showed a noticeable hollowing in the middle of the road, caused by rainwater flows. During rainfall events, the water flow on the roads was relatively high, and when these roads were investigated after a prolonged or heavy rain event, the flow paths of the surface water were clearly visible in the soil. Some lower elevated points on the roads were also filled with water, which formed puddles. While erosion was visible throughout the entire school area, it was most severe on the roads as other areas showed erosion signs to a lesser extent. During rainfall, a large flow of water could however be seen in the residential areas, flowing from west towards the residential building for volunteers. The field observations of flow paths corresponded well with the simulated results obtained from Scalgo Live.

Another commonly observed issue was the accumulation of water at several locations after rainfall. Since the terrain gently slopes towards east where the residential area for teachers and volunteers is located, this part of the land area experienced the most significant water accumulation. However, smaller scale accumulations of standing water were also observed in other places around the school, for instance outside the school building or outside the dining hall for students. These smaller water accumulation points tended to drain relatively quickly, and they were typically dried out by the afternoon following a night of heavy rainfall. In contrast, the areas with accumulated water in the residential area for volunteers and teachers could often remain for a day or two after a rain event before fully drying, especially when rain events occurred on consecutive days. The drying time of pooled water was heavily influenced by the intensity and duration of rain events. During extended rain events lasting a full day or more, water drained more slowly. Areas that were covered in vegetation were notably less prone to water accumulation, most likely due to increased infiltration of the plant cover. Although accumulation of water was visible at the site, it was not considered as problematic as the simulations from Scalgo Live showed, especially not in the residential areas. This could be explained by the multipath effect being noticeable when sampling in these areas, as there were many buildings or other obstacles where satellite signals could bounce off. This likely affected the quality of the collected GPS data, making the simulation results from Scalgo Live less accurate in these areas.

5.4.3 Proposed flood mitigation strategy

Since both the results from Scalgo Live and the field observations indicated destruction of roads as a critical challenge, the proposed mitigation strategy focuses on reducing erosion and water flow on the roads. The problem of heavy rain leading to soil erosion on the road is worsened by the fact that there is no water drainage system or any form of water diversion from the road. A practical and cost-effective solution to this problem would therefore be to implement a system that diverts the water away from the roads. The diversion system should ideally be vegetated so water can infiltrate into the soil and be absorbed by plants. The diversion system that would be most suitable at Tumaini Open School is to construct swales, which are shallow vegetated channels, along both sides of the main road. These would slow down surface runoff, promote infiltration, and reduce the erosive effect of water flowing on the roads. Figure 5.4 shows the simulation results from the Scalgo Live after swales with a depth of 1 m and a width of 2 m had been modelled on both sides of the main road. The updated simulation shows that the surface water now flows alongside the road rather than directly on it, which achieves the intended aim.

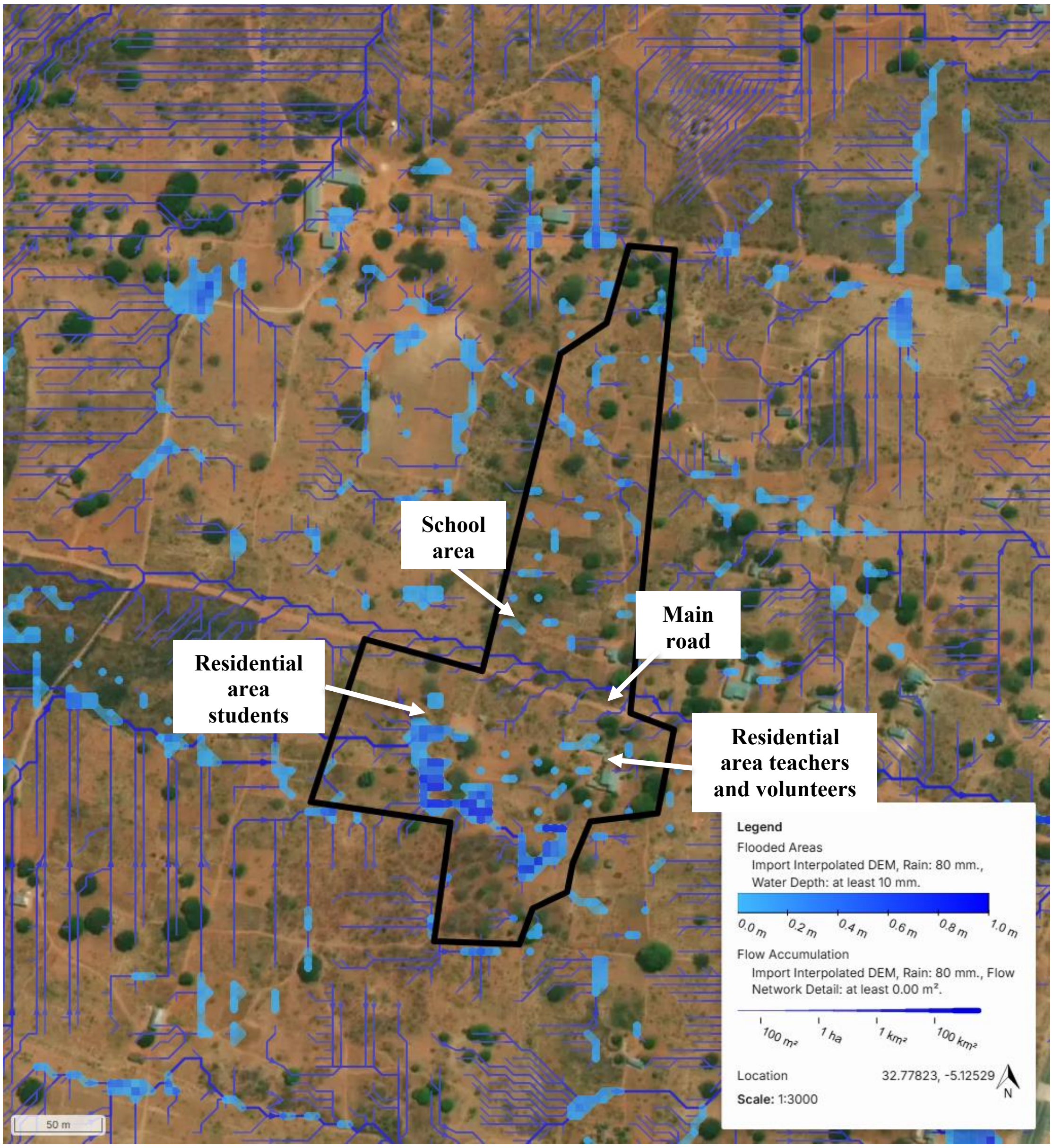

Figure 5.4: Flooded areas and water flow accumulations after constructed swales along the main road during an 80 mm simulated rainfall event at Tumaini Open School.

The benefits of swales extend beyond flood mitigation as they also serve to filter stormwater. This can lead to improved groundwater quality and contribute to groundwater recharge. However, to fully extract the benefits of the swales, the roads themselves must first be restored and redesigned in a way that enables water on the roads to flow into the swales. Specifically, the roads should be designed with a gentle slope from the center towards the edges. This would guide the water into the swales instead of allowing it to carve a channel in the middle of the roads.

Although there were several SUDS that could be implemented to mitigate flood risks at Tumaini Open School, swales were identified as the most appropriate solution. This decision was based on the size of the school area being under 4 ha, as well as the significant soil erosion issues present on roads. Furthermore, the possibility of reducing the pollutants in stormwater was also a major benefit that was considered when deciding the solution. Another aspect that makes swales a suitable solution to implement at the site is the fact that the measured infiltration rate at the site exceeds the recommended minimum infiltration rate for swales, which is 12.7 mm/h. However, a potential future challenge is the risk of litter accumulation in the swales. There is therefore a need for more effective waste management at the site to ensure that the swales remain functional. Installing garbage bins around the school area and educating the students at the school about the importance of keeping the environment clean could potentially reduce this risk of littering in the swales.

It is also important to note that swales must be implemented in areas beyond the boundaries of the school area to be effective. If only the roads within the school grounds are improved, surface runoff from upstream areas can still damage the roads in the school area. Furthermore, fixing the internal roads without improving the connecting roads to and from the school would not improve accessibility as connecting roads are just as important. Therefore, this measure needs to be implemented collectively and be part of a broader initiative involving cooperation from other members in the surrounding village.

Although the modelling in Scalgo Live showed more water accumulation than the field inspections, both indicated accumulation to some extent. During rainfall, the volunteers' house was massively exposed to large water flows on its west facing facade. There is currently a drainage system in place to minimise water damage for this building, however, no such systems exist for any of the other buildings. Even though the volunteers' house is the only building that currently risks being damaged from floodings if a drainage system is absent, climate change and changing rainfall patterns in the future can increase vulnerability of other buildings over time. Therefore, drainage systems should be incorporated into the design and construction of new buildings that are constructed at the school.

5.4.4 Discussion of method

The method used for the flood analysis proved to be both suitable and effective for identifying important problem areas and developing appropriate mitigation strategies. The combination of field observations, DEM analysis, and hydrological simulation in Scalgo Live provided a comprehensive understanding of the flooding dynamics at Tumaini Open School. However, several limitations and areas for improvement were identified, both in terms of data collection and modelling techniques.

When collecting elevation data with the GPS, it was noted that the satellite connection varied between different data collection activities. Even though the highest possible GNSS-accuracy was established before every sampling session, the number of available satellites differed. Generally, the GPS satellites performed the best, and the handheld GPS consistently received signals from at least five of them. The Galileo system was the second most reliable and always had at least one satellite signal available, while the GLONASS system was the least reliable in terms of signal availability, which was sometimes entirely absent. In some areas, a multipath effect was observed in the collected data following the sampling. This was most prominent in the living areas where buildings and large trees could disturb the LOS, especially in the residential area for teachers and volunteers. As a result, the water accumulation near buildings and structures may not have been fully captured in the modelling results, which may potentially have resulted in an overestimation of flood-prone areas in these zones in the model. The field observations confirmed, and in some cases, refined the interpretations from the simulations. For this reason, the Scalgo Live simulations and the field observations complemented each other and together provided a more complete understanding of the flood risks at the school.

An improvement to the method would have been to collect more elevation data. This would have increased the accuracy and reduced the impact of the multipath effect or other disturbances. However, this was constrained by the scope and time limitations of the project. Despite this, the data collection was considered sufficient under the circumstances. If the study would be performed again, it would benefit from conducting elevation sampling during the dry season, when reduced vegetation would improve accessibility and facilitate the sampling process. Additionally, using laser measurers or scanning the area with a drone would have provided more precise measurements. These options were not feasible within the budget or time frame of this project but are worth considering for future studies.

5.5 Water quality analysis

The rain intensity for the rain activity when the rainwater samples were collected was calculated to 6 mm/h, which is classified as a moderate rainfall. The intensity of the rain is, however, not very important in this case as no sampling of the first flush was performed, which is when the rain intensity is an important aspect. The results presented in this chapter are the compiled results where an average of the three samples from each collection points have been calculated. The full results for each sample can be seen in Table E.1 in Appendix E. Apart from showing the measurements of pH, turbidity, and conductivity, they also present the measured temperature for the samples.

5.5.1 Analysis of pH

The analysis of pH in the different sampling points can be seen in Table 5.3. The pH of the samples varied from 5 and 10, but no variation of the pH was shown for the 3 samples that were collected in each sampling point. As expected, the samples with the lowest measured values were the rainwater samples, while the samples containing greywater had the highest pH. All the rainwater samples that were analysed, except for the rainwater sampled from the ground, had a pH of 5. This is lower compared to what the sampled water from the plastic tank and tap showed, as these were either a pH 6 or 7 when analysed. This is reasonable as rainwater is generally slightly acidic. Since rainwater with a pH lower than 5.6 is classified as acidic rain there is a possibility that the rain at the site is acidic. However, it is important to note that the method used only expressed the pH within one unit, which means there is an uncertainty of the exact value. Therefore, it is not possible to draw a conclusion on whether the rain in the area had a normal pH value, or if it was acidic.

Table 5.3: Analysis of the pH value in the collected water samples.

Sampling point	**pH**
Water accumulating on ground	6
Rainwater directly from sky	5
Rainwater from roof: Volunteer's house	5
Rainwater from roof: Teacher's house	5
Rainwater from roof: School building (west side)	5
Rainwater from roof: School building (east side)	5
Rainwater from roof: Student's dormitory	5
Rainwater from roof: Student's dining house	5
Municipal water from plastic tank	7
Municipal water from tap	6
Water from shallow well	5
Greywater from handwashing clothes	10

The samples collected from the greywater from laundry showed that this water was alkaline as it had a pH of 10. This was expected beforehand as this water contained soap and washing detergent, which are both alkaline substances. Letting this water out in the nature can lead to pollution and using it for irrigation before treating it can cause crops to die.

5.5.2 Analysis of turbidity

The turbidity varied greatly between the samples where the highest turbidity measured was around 800 FNU, while the lowest measured value was under 1 FNU. A compilation of the measured turbidity in all the sampling points can be seen in Table 5.4. The source of water that generally resulted in the lowest turbidity was the rainwater. All the samples of rainwater either directly from the sky or runoff from the roofs had a turbidity of less than 1,07 FNU, with all of them but one being even less than 1 FNU. Since the range of turbidity was less than 1 FNU for all the rainwater samples collected from the roofs, the quality of the water collected from each roof was considered equivalent. Even though the living areas for both students and teachers were prone to wood burning, no traces of this activity could be seen when measuring the turbidity of the water samples from the roofs in these areas. Furthermore, samples from the roof areas located close to high trees, like the teachers' house and the students' dining house did not show higher turbidity than samples from the roofs not surrounded by large trees, for instance the school building. When considering the turbidity of sampled water, no conclusion about which roof is most suitable for RWH could therefore be drawn.

There was no significant difference between the samples of water collected directly from the sky and the samples collected from the roofs. This indicates that roofs are a suitable collection surface when harvesting rainwater in the area, as it did not increase the turbidity of water. However, it is important to note that the water sampling was performed during the rainy season when rain events occur frequently, meaning there is less time for pollutants to attach to the roof surfaces in between rain activities. Furthermore, at the time of sampling it had already rained constantly for several hours, resulting in no first flush samples being collected. This means that dust, leaves, or other debris or pollutants had plenty of time to be rinsed from the roofs, leaving the roofs relatively clean at the time of sampling. On the other hand, rainwater will only be harvested during the wet season when these are the conditions most of the time.

Table 5.4: Analysis of the turbidity in the collected water samples.

Sampling point	**Turbidity (FNU)**
Water accumulating on ground	203
Rainwater directly from sky	0.76
Rainwater from roof: Volunteer's house	0.49
Rainwater from roof: Teacher's house	0.08
Rainwater from roof: School building (west side)	1.07
Rainwater from roof: School building (east side)	0.14
Rainwater from roof: Student's dormitory	0.38
Rainwater from roof: Student's dining house	0.25
Municipal water from plastic tank	3.17
Municipal water from tap	3.77
Water from shallow well	8.41
Greywater from handwashing clothes	759

The rainwater that was collected at a point of accumulation on the ground expectedly had a higher turbidity as it had been in contact, and partly mixed, with the ground surface. Similarly, the greywater from washing clothes also had a very high turbidity. The high turbidity for the greywater needs to be considered when proposing a solution for greywater management at the site.

The turbidity of the water collected from the tap and the shallow well was higher than the turbidity in the rainwater, although it was still seen as rather low. The water from the tap and the plastic tank, that is partly used for drinking, does not reach the ideal guidelines from WHO (2017) of being under 1 FNU. However, it is still classified as sufficient as none of the measured values exceed 5 FNU. These samples are all within the Tanzanian drinking water guidelines as the turbidity did not exceed 25 FNU (United Republic of Tanzania, 2007). Even though the ideal guidelines for drinking water by WHO are met for the rainwater, there is no plan to use the harvested rainwater for drinking. This is because turbidity can only give an indication of the level of pollution, but the absence of other contaminants cannot be guaranteed. To decide the suitability of using the harvested rainwater for drinking purposes, more parameters would have to be tested, including microbial contamination as well as traces of metals from the roof materials.

5.5.3 Analysis of conductivity

Even though conductivity is affected by temperature, the temperatures of the different samples were all similar, spanning from 22.8 °C to 26.1 °C, making the conductivity of the samples comparable. Table 5.5 expresses the results of the conductivity in the samples. The table shows that the conductivity varies greatly between the different water sources. All the samples of rainwater have a rather low conductivity and are alike, except for the rainwater accumulated on the ground which is slightly higher. The tap water and the water from the shallow well are also comparable to each other, and in relation to the rainwater, these samples have a higher conductivity. The water source that stands out from the rest is once again the greywater generated from laundry by hand. The conductivity for it is in the scale of more than 1 000 times higher than in the rainwater samples, and around 20 times higher than in the water from the well or municipal network. This indicates a high presence of dissolved ions, like salts or inorganic substances. Using this untreated water for agricultural purposes would be unwise as it can lead to salinisation of the soil and death of crops. The greywater from laundry could also potentially be harmful for humans since the measured conductivity exceeds the recommended values for drinking water. It should therefore not be consumed and should be handled with diligence.

Table 5.5: Analysis of the conductivity in the collected water samples.

Sampling point	**Conductivity (µS)**
Water accumulating on ground	60
Rainwater directly from sky	4
Rainwater from roof: Volunteer's house	3
Rainwater from roof: Teacher's house	5
Rainwater from roof: School building (west side)	3
Rainwater from roof: School building (east side)	3
Rainwater from roof: Student's dormitory	6
Rainwater from roof: Student's dining house	3
Municipal water from plastic tank	205
Municipal water from tap	205
Water from shallow well	266
Greywater from handwashing clothes	5 547

5.5.4 Discussion of results and method

The results from the water quality analysis indicate that there are minimal variations between the rainwater samples collected from the different roof surfaces. Furthermore, no significant difference could be seen between the rainwater samples collected from the roof and those containing rainwater directly from the sky. The lack of clear variation suggests that all investigated roofs performed similarly in terms of water quality under the conditions of this study, hence the measured parameters did not provide a scientific basis for determining the most suitable roof for harvesting rainwater based on pollution levels. This outcome is most likely influenced by the meteorological conditions at the time of sampling, since the sampling took place during the rainy season when rainfalls remove pollutant accumulation on roofs. It is important to note that these findings may not be applicable to drier periods when roof surfaces tend to be more polluted. For future work on long-term implementation of RWH systems, it may be beneficial to carry out sampling across multiple seasons to better understand how seasonal variability influences water quality. Furthermore, the analysis also showed very small or non-existent differences in water quality between the municipal water directly from the tap and what had been stored in a plastic tank. This indicates low water quality degradation through this storage method, making it suitable for continued use.

There were also major challenges related to conducting the field research in a remote and resource-limited context. While basic tests such as pH, turbidity, and conductivity could be done with portable and simplified equipment, more complex and precise chemical analyses often require laboratory equipment and access to chemicals such as reagents. For instance, the pH strips used to measure the pH value only provided results within one pH unit. A more precise result could have been acquired by using a pH-meter instead. However, this was not brought due to risk of breaking it during transportation, as well as the electrodes sensitivity to being carried in a specific, acidic liquid. Furthermore, if the analysis would have been performed in a laboratory environment instead, more parameters could have been tested, and more accurate results could have been obtained. Ion chromatography would have been used to test the presence of ions in the water. Furthermore, microbial analysis of the water would have been performed to assess the level of pathogens and bacteria.

The original plan for the water quality analysis included testing for iron, nitrogen and phosphorus content in the water, in addition to pH, turbidity and conductivity. These were considered relevant due to their potential presence in rainwater and local water sources and their environmental and health-related effects. Despite their relevance, it was not possible to include these parameters in the analysis due to logistical limitations. The chemical reagents required for these tests were not available locally in Tanzania and transporting them from Sweden proved difficult. Due to safety regulations, travel restrictions and customs limitations on shipping or carrying chemical substances internationally, it was not feasible to perform these additional tests during the field work period. An attempt of sending the required reagents with a courier was made but without any luck. The high costs for sending the reagents with a special courier could not be justified, partly since there would still be a possibility of the material not reaching the destination, but also because the results would still be of lower quality compared to laboratory results.

The possibility of bringing water samples back home to Sweden and analysing them in the laboratory at Chalmers was also considered but concluded to not be a suitable solution. First, the samples must be relatively fresh when analysing. This could not be guaranteed as most rain events occurred during night, which limited the times when rainwater sampling was possible. To time the sampling right upon departure from Tumaini Open School would therefore have been difficult. Secondly, the samples had to be stored in certain conditions between sampling and analysis, which would have been difficult to achieve on a 35-hour long journey where there was no access to a fridge to keep the samples cool. The only possible solution was therefore to analyse the samples on site, which unfortunately came at the expense for the number of parameters that could be analysed. The absence of an analysis of iron, phosphorus, nitrogen or any other parameters in the water samples does not take away the conclusions of this study, but it does limit the ability to fully assess the potential for contamination in harvested rainwater and other water sources. However, the parameters that could be analysed for the samples were still useful as they gave an indication of the pollution level in the water. In future studies, potential solutions could include establishing partnerships with local or regional laboratories, sourcing reagents from within East Africa, or coordinating with universities or institutions in Tanzania to conduct joint testing.

5.6 Rainwater harvesting solution

The proposed solution for RWH at Tumaini Open School is to collect rainwater from roofs and store it in a tank, where it is distributed further. This solution is in line with the school's goal to increase their self-sufficiency by reducing the reliability of municipal water supply. The harvested water should primarily be used for irrigation and construction work. When designing the RWH solution, both the most suitable roof collection surfaces and the placement of the water storage tank had to be considered. This section includes the assessment, design, and implementation plan for the proposed harvesting system.

5.6.1 Most suitable roof collection surfaces

The water quality assessment of water samples collected from roofs did not show any significant differences in quality. As a result, other aspects had to be considered when deciding which roofs to harvest rainwater from, including roof size, shape, proximity to sources of pollution and water demand in the area. The three main areas to consider for water collection were the educational area, the residential area for students, and the residential area for teachers and volunteers. There were other buildings present at the site, but these were not considered suitable as they were either too small or old and rusty, which could impact efficiency and water quality negatively. The shapes and sizes of the roofs in each of these areas can be seen in Figure 5.5. For the students' living area, two total roof sizes are given: one for the current situation, and one for when the second dormitory under construction is finished.

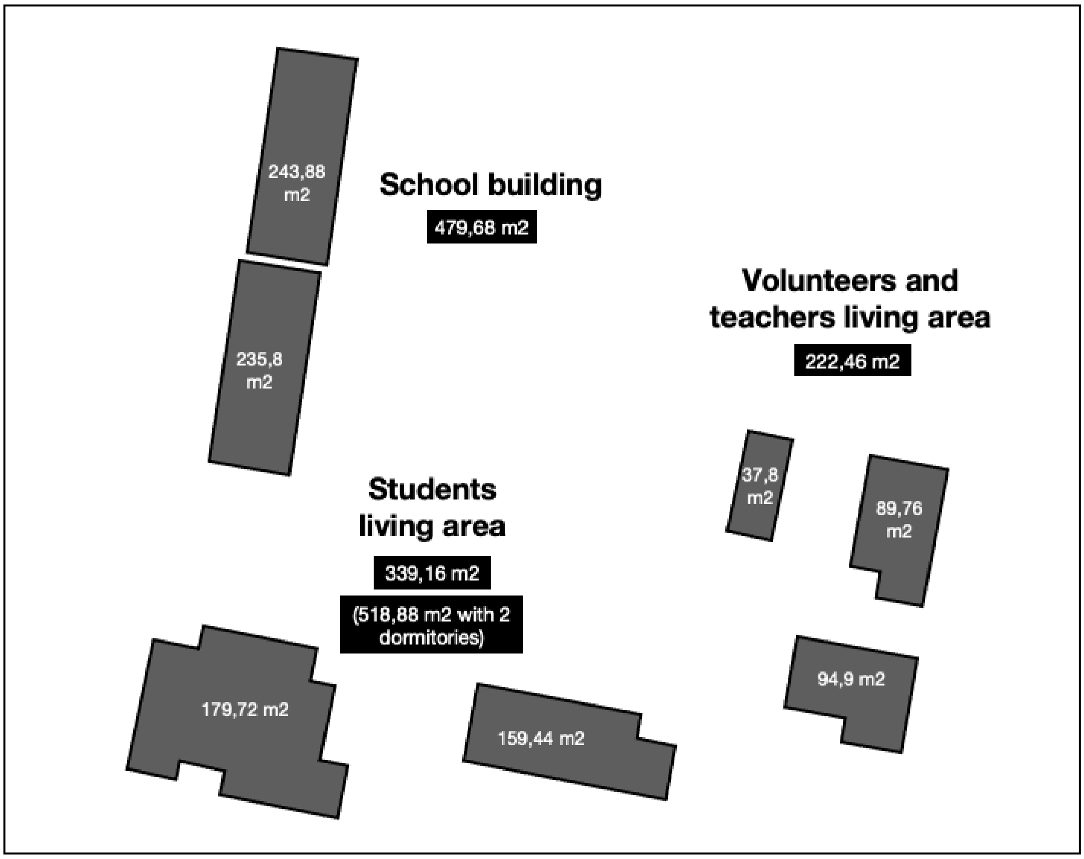

Figure 5.5: Measured roof areas for each roof as well as the total roof area for each subarea at the site. For the students living area, two alternatives are shown: the first is the existing room area, and the one in brackets is the estimated future roof area when the dormitory under construction is done.

When looking at the collective roof areas for the three main areas, the area with the largest roof surface area is the school building. However, the total roof surfaces in the students' residential area are almost as large, and if the roof area for the soon-to-be finished dormitory right next to the existing roofs was to be added, then this area would instead be the largest. Regarding the roof areas in the living area for teachers and volunteers, this is the smallest and therefore the least suitable for RWH in this aspect.

When considering the shapes of the roofs and their proximity to each other, the school building is the most suitable option for RWH. The two roofs there are rectangular and placed right by each other, while the roofs in the other areas are both further away from each other and irregularly shaped, especially the students' dormitory. A more uniform roof shape would make the fittings and installation of gutters onto the roof ends easier and likely minimise leakage due to less joints. Furthermore, the steep roofs at the students' dormitory, the dining hall, and the volunteers' house would result in a heavier flow of water from the roofs, increasing the risk of an overflow of water in the gutters during high intensity rain events.

Water consumption is also an important consideration, and when looking at the water usage in the different areas, the usage is clearly highest in the living area for the students. The usage in the educational area is almost half of that, while the water consumption in the living area for teachers and volunteers is even lower. From a consumption perspective, it would be sensible to harvest rainwater in the students' living area or the educational area, since this is where the largest volumes of water are consumed.

Another factor to consider is rooftop contamination. Environmental conditions suggest that the roofs in the residential areas can be expected to be more polluted than in the educational area. Even though the water analysis did not show any significant difference in water quality between the investigated roofs, it is still something that needs to be considered. Animals such as birds are often seen on and around the roofs in the living area for volunteers and teachers, which can lead to pollution on the surfaces. Furthermore, the frequent wood burning occurring in the residential areas for students, teachers and volunteers is also a potential source of contamination, as ashes and particles can settle on the roofs. When considering pollution from trees, there is no area that sticks out as worse or better since trees are present in the entire school area.

When considering all the aspects mentioned above, the most suitable solution would be to harvest rainwater from the roofs of the school building. It is the current largest roof area, it has a simple and efficient shape for gutter installation, the water demand in the area is high, there is no wood burning in or around the building, and there are relatively few trees and free roaming birds.

5.6.2 Placement of tank

The school area is also considered the most suitable location for placing the water storage tank, both in terms of functionality and safety. It is the most open and spacious area, which means the construction of a large storage tank there would not ruin the aesthetic of the campus area or make it feel too crowded.

When placing the water storage tank, it is important to consider the proximity to possible contamination sources such as septic tanks, graves, or areas with free roaming animals. In the students' living area, there are several graves right next to the dining hall, meaning that it would be unsafe to place a water storage tank too close to these. The free roaming animals present in the teachers' and volunteers' living area makes that area unsuitable for a water storage tank as well. All three main areas have one septic tank each. However, since the living areas are so compressed, the most suitable area would be the school area since this is where the distance between the septic tank and the water storage tank would be the largest. Additionally, the school area is also seen as the area with the lowest risk of pollution from untreated greywater. In the living areas, the students, teachers, and volunteers all release untreated greywater generated from showering, cooking, and laundry into the ground in several locations. In the school area, only greywater from handwashing and cleaning of facilities is released into the environment.

The water storage tank should be located on the west side of the school building, in the middle where the two roofs connect. Placing the tank on this side would result in at least 50 m between the storage tank and the nearest septic tank, fulfilling the Tanzanian guidelines. The distance to the nearest grave would be around 80 m. Ideally the distance to the graves should be larger, however, the graves are located at a lower elevation which limits the risk of them potentially contaminating the water in the storage tank. The septic tank is located at a similar elevation as the proposed location for the storage tank. At this location, there are no constructions, agricultural crops or infrastructure that would have to be moved or destructed when constructing the water storage tank. As this is on the back of the school building, this placement would not disturb the aesthetics or be in the way of anyone or anything.

The tank could also be placed in the southern end of the school building. This location would ensure the largest distance to a septic tank with over 75 m to the closest one. The distance to the nearest grave would be around 70 m. The reason for not suggesting this placement is that the roofs on the school building are disconnected and at different heights, which is visualised in Figure 5.6. The southern roof is slightly higher elevated than the northern roof as seen in Figure 5.6c. If the water storage tank is placed at the southern end of the school, transporting water from the side with the lower elevated roof to the side with the higher elevated roof will be a challenge.

Figure 5.6: Visualisation of the gap and height differences between the two roofs on the school building. a) The facade on the west side. b) The facade on the east side. c) The gap shown from another perspective on the east side. The southern roof is visibly higher elevated than the northern roof.

As seen in Figure 5.6a and b, the roof on the facade facing west does not have a large eave, while the facade facing east does. Pipes and gutters can be installed from the lower elevated roof on the west side along the wall, preferably below the windows, to lead the water from the lower roof to the storage tank. This would solve the problem of leading water from a lower roof to a higher roof. However, on the east side, this is not possible as the gutter from the lower elevated roof then would be in the way and affect both the aesthetical aspects as well as the functional aspects of the building. If the storage tank is placed at the southern end of the school, it would therefore only be possible to harvest rainwater from 75% of the school building's roof area. A sketch of how this would look is shown in Figure F.1 in Appendix F. This is not an ideal solution as it does not harvest rainwater from the full roof area, and therefore, this is not the solution that is proposed. However, if any further investigations of the study concludes that the proposed solution is not possible, this is the alternative that is seen as the second-best option.

5.6.3 Design of the rainwater harvesting solution

The proposed RWH system at the school is designed to collect, transport, store, and distribute rainwater from the roof of the school building. The design is based on passive water collection, combined with pumping mechanisms for distribution and includes several features to ensure the quality and safety of the stored water.

To collect rainwater from the roofs, gutters should be installed along the eaves of the school building roof. The gutters will then channel the rainwater by gravity towards downpipes to lead the water to the main storage tank. Since the harvesting system relies on natural fall from gravitation, the gutters and downpipes must be angled to ensure a sufficient and consistent slope. With the tank being placed in the middle of the backside (west side) of the school building, the water from the roofs on the front side will have to be transported to the tank via the short sides of the building. Since the end of the eaves are slightly higher elevated on the east side compared to the west side, ensuring natural fall when transporting the water from the frontside along the short sides to the backside should be easily achieved.

The peak flow of the system resulted in a maximum runoff rate of 24 L/s, which represents the peak flow from the entire roof during a short intense rain event. This is the design flow that was used to decide the size of the pipe leading the rainwater from the roofs to the tank. However, the design flow used in the dimensioning of the gutters attached to the eaves was only 12 L/s as the catchment area for these gutters is halved because these pipes only receive roof runoff from maximum half of the total roof area. Using SMACNA's Downspout & Gutter Sizing Calculator, a dimension of 125 mm x 150 mm, which is a standard gutter size, was selected for all the gutters on the school building. The diameter of the downpipes leading rainwater from the gutters on the roof into the tank was chosen from the design guide from MGMA. The most suitable diameter was 150 mm, which can manage a maximum flow of 31.6 L/s. This capacity is required to manage the peak flow of 24 L/s. These gutter and pipe dimensions provide a buffer for minor blockades or rain events with higher intensity.

A simple model of the school and the design of the RWH solution is illustrated in Figure 5.7 and Figure 5.8. This design enables water harvesting from 100% of the school's roof without compromising the aesthetics or the accessibility of the school building.

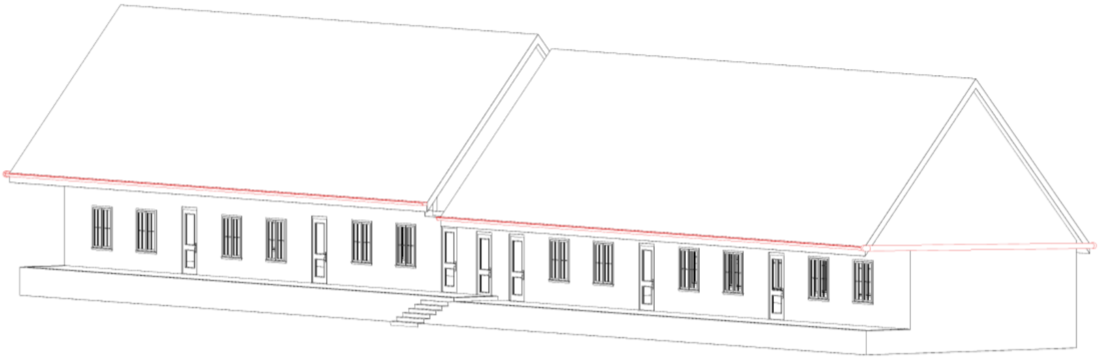

Figure 5.7: Model of the east facade of the school building. The gutters, shown in red, transports the water from the east side along the short sides to the west side.

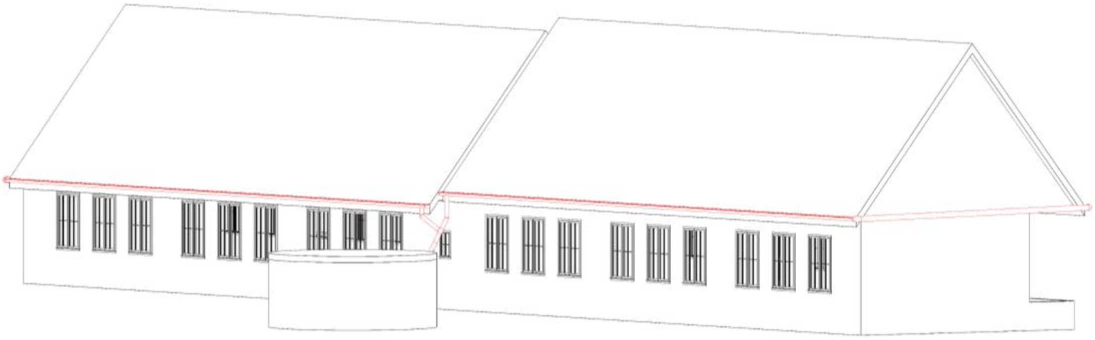

Figure 5.8: Model of the west facade of the school building. The water is led from the east side to the west side through gutters, shown in red in the model. The downpipes leading the water from the gutters to the storage tank is also shown.

To protect the quality of the collected rainwater, a first flush diverter should be integrated into the gutter system. This component will ensure that the initial runoff, which may contain dust, debris, and bird droppings from the roof, is diverted away from the storage tank. The first flush diverter is installed on the downpipe and consists of a closed pipe that sticks out from it. When a rainfall starts, the initial flush of rain enters the enclosed pipe. Once the diverter pipe is filled with the water from the first flush, the pipe entrance closes, and water instead flows into the water storage tank. This way, the more polluted water can be separated from the rest, and only cleaner water from the later stages of the rain event enters the tank. The first flush diverter will be manually operated and must be emptied between rainfalls. The design of the first flush diverter is shown in Figure 5.9. This figure only shows the concept of the first flush diverter, and the diverter pipe is not scalable.

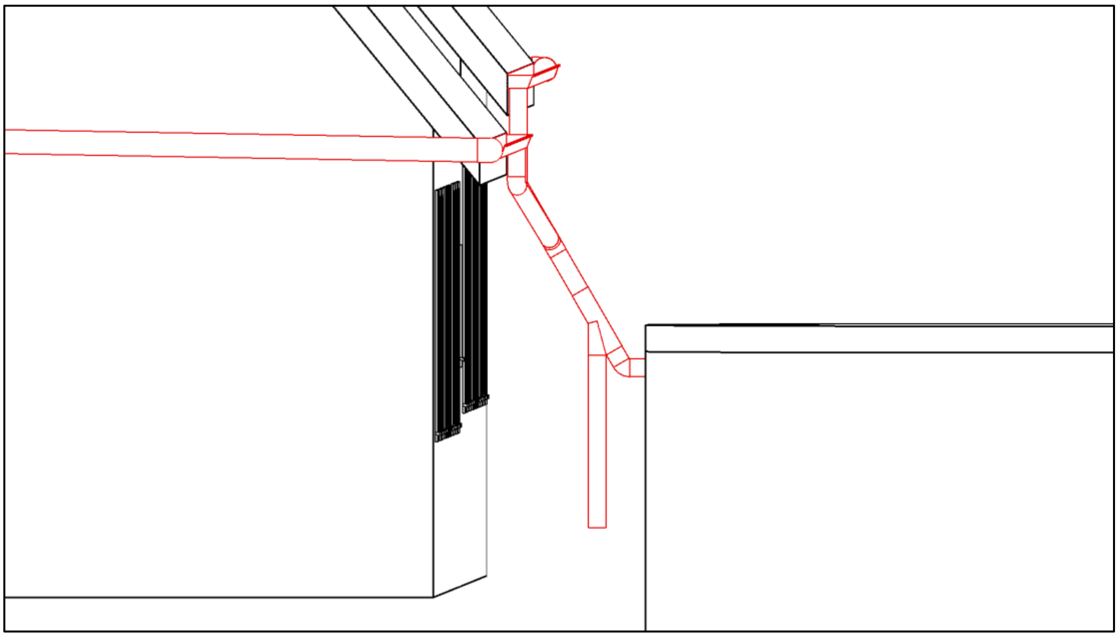

Figure 5.9: Design of the first flush diverter in the RHW system. The diverter is connected to the pipe leading rainwater from the roof gutters to the storage tank.

In addition to the diverter, mesh screens should be installed at the lower ends of each downpipe to block leaves and larger debris from entering the system. Regular cleaning of these screens will be necessary to prevent clogging and overflow. To further improve water quality and ensure safety for water intended for consumption or hygiene purposes, the system should also include a basic filtration step such as sand filters, UV disinfection or chlorination. Since the collected rainwater is not intended for these purposes in this case, these additional filtration steps are not deemed mandatory for the intended uses of irrigation and construction work. However, it is possible that these filtration steps could still be necessary, especially considering the uncertainty in the water quality analysis. Future water quality analysis can be applied to evaluate the need for additional treatment or filtration.

To avoid failure in the rainwater harvesting system, maintenance is another important factor to consider during design and operation of the system. It is especially important to inspect and clean gutters, mesh screens, and the first flush diverter during the rainy season. Furthermore, the tank also needs to be inspected for cracks or leaks. Periodic water quality testing, especially for coliform bacteria, pH, and turbidity, is also recommended to ensure that the water remains safe for non-potable use. The maintenance of these systems requires knowledge and time from the people at the school. A maintenance plan should therefore be developed and implemented upon implementation of a RWH system, and the local staff should be trained in basic upkeep practices. If external support is needed for larger repairs, relationships with local contractors should be established early. Furthermore, community engagement is key. Involving students in maintenance routines can increase awareness and promote a culture of sustainability. This will also help in reducing maintenance failure and misuse of the system.

After collection and storage, the water will need to be transported to usage points, such as elevated plastic tanks. To achieve this, a submersible or surface pump should be installed inside or near the concrete storage tank. The pump will transfer water to an elevated 5 000 L plastic tank placed on a concrete block, just like the plastic tanks around the school where water is pumped from the municipal water supply network. The plastic tank, which should be placed next to the concrete tank, enables distribution of water through gravity. The placement of this water point is beneficial for the water usage both in and around the school area, as well as by the residential area for the students, since it is placed in the close vicinity to all these. Pumping water from the concrete tank to smaller elevated plastic tanks next to it also further increases the storage capacity of the RWH system as even more rainwater can be stored before the tanks are filled.

5.6.4 Design of water storage tank

The design of the water storage tank is an important element in the RWH system since it impacts the quality, quantity, and reliability of the water supply. Several factors have been considered in the choice of tank material, size, placement, and functionality. These are based on site-specific conditions at Tumaini Open School and lessons learned from nearby implementations.

The proposed water storage tank will be constructed from concrete, which is deemed to be the most suitable material for several reasons. Firstly, it is well suited in a local context since concrete tanks are commonly used in nearby facilities with similar environmental conditions. Another advantage is alkaline buffering since concrete can neutralise the pH of acidic rainwater during storage in the tank. This can naturally reduce corrosiveness, which extends the life of the tank and pipes. Furthermore, concrete is highly durable and resistant to weathering, UV radiation, and physical damage, which is beneficial in regions with high temperatures, intense sun exposure, and potential floodings. Lastly, cost-effectiveness and local expertise are also major advantages. Concrete can be sourced and constructed locally, which supports the local economy and reduces transportation costs. Construction workers in the area are also familiar with concrete tank installation, which simplifies logistics. Other materials were considered but found less suitable. For instance, metal tanks are relatively expensive and pose a risk of corrosion, especially when used with acidic water. Additionally, they do not insulate well against the heat. Plastic tanks on the other hand, are affordable and lightweight, but offer less protection against temperature fluctuations and are more prone to cracking and damage in extreme weather events. For these reasons, the ground-level tank will be made from concrete, while any elevated or roof-level distribution tanks will be made from plastic due to ease of installation.

It is important that the storage tank is large enough to capture and hold sufficient rainwater during the rainy seasons, while also avoiding an excessive size that would increase costs or cause space constraints. The size of a storage tank should also be proportional to the size of its catchment area. Since the harvested rainwater is intended to mainly be used for irrigation and construction, the demand of 975 lpd was used when dimensioning a suitable tank size. Although the school is planning on expanding, the water demand for irrigation and construction was assumed to stay at a constant level. When adding this as an input for the water demand and varying and adjusting the volume of the storage tank, the coverage percentage for each day of the year could be calculated. According to the Excel design tool used to find a suitable size for the tank, a volume of 176 000 L is required to constantly achieve a 100% coverage of the water demand for irrigation and construction at the school throughout the whole year.

However, this is not a reasonable size as it would be too costly to construct and require too much space.

A more reasonable size of 60 000 L is proposed. This size is not large enough for covering the demand for the whole year, but instead result in a full coverage 70% of the time, which is still considered sufficient. The relationship between water storage tank size and coverage rate was mostly linear and is illustrated in Figure G.1 in Appendix G. The dimensioning of the tank is also reasonable when considering the dimensions of the RWH system at the nearby school. The coverage rate for a 60 000 L tank when looking at the rain data from the past 25 years can be seen in Figure 5.10. A pattern seen in this graph is that the tank will be empty from around June to October during the dry season. The graph also illustrates that the coverage rate is mostly at either 100% or 0%, and not so much in between. This is explained by the distinct differences between the dry and wet seasons in Tabora. The tank will generally be completely full during the wet season and completely empty during the dry season. A way to fully utilise the potential of RWH in this case could be to prioritise the construction work, which requires large volumes of water, to take place during the wet season. This could shift the water demand to increase during the wet season, when there is an abundance of rainwater, and at the same time decrease the water demand during the water-scarce dry season. This could in turn lead to a higher coverage rate, enabling better opportunities for irrigation during the dry season.

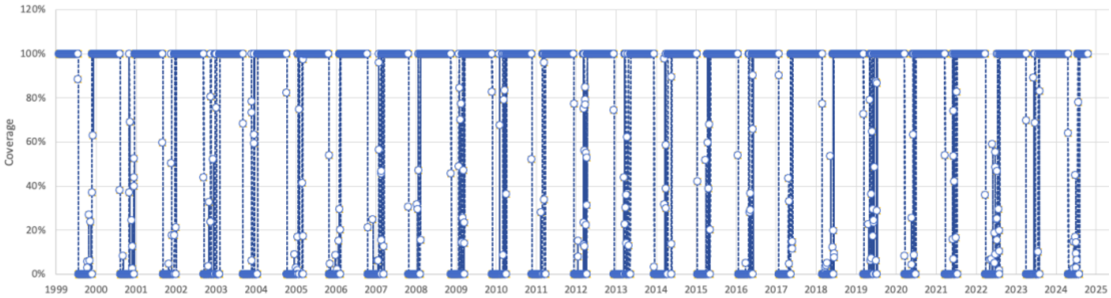

Figure 5.10: Graph showing how the coverage rate for a 60 000 L tank would have variated based on weather data for the past 25 years.

There are several important considerations for the tank design. The first is to place the tank partially underground to help stabilise internal water temperatures, protect the tank from UV radiation, and reduce the visual and spatial footprint. The tank must also be fully closed with a sealed lid to prevent contamination from animals, insects, and debris, and to reduce the risk of mosquito breeding. The lid should be lockable and well-fitted. A secure manhole should be included for cleaning and inspection purposes, without needing to open the entire lid. Internal cleaning in the tank must be done regularly, at least once a year before the rainy season. The storage tank must also have an outlet at the top in case of excessive rainfall to prevent overflow. It is also recommended to apply internal and external weatherproof plastering to prevent seepage and structural weakening.

5.6.5 Discussion of the rainwater harvesting solution

The proposed RWH solution at Tumaini Open School is a practical and sustainable step towards increased self-sufficiency. By collecting and using rainwater, the school can reduce its dependence on municipal water supply and increase resilience to service interruptions, and potentially also water-scarce dry seasons. Reducing the reliance on the municipal water through RWH can improve the sustainability of the school socially, economically, and environmentally. Social sustainability comes from increasing the reliability of the water supply system. There are currently a lot of uncertainties regarding when the municipal water supply system is functioning, which can cause worries or problems among the residents of the school. The water management is also an economical aspect as RWH can reduce the money spent on the municipal water. If RWH can be implemented, less municipal water is needed, which lowers the usage of this water at the site. This lowered water consumption also increases the environmental sustainability.

For the RWH system to function optimally, some aspects need to be considered before implementation. The first aspect is regarding feasibility and long-term functionality. The idea of harvesting rainwater from rooftops is not new, and the solution has been implemented at other nearby schools and facilities, though not without challenges. In one case, a nearby school constructed a RWH system that eventually fell out of use due to lack of maintenance. To avoid a similar outcome at Tumaini Open School, it is of importance to incorporate responsibilities for maintenance and regular inspection, as well as training staff on how the system operates. The long-term collaboration between Tumaini Open School and EWB does, however, limit the risk for a lack of maintenance of the system to some extent. If projects by EWB are carried out continuously at the site, there is a possibility of volunteers also helping with the maintenance or at least reporting what type of maintenance is needed. This RWH solution is also relatively common in the area, which increases the chances of local availability of maintenance knowledge.

Furthermore, the design must be carried out in a way that considers both short-term needs and long-term scalability. As the student population grows from the current 55 students to a projected 400 in the future, the overall water demand at the school will rise significantly. This entails that careful planning of the tank capacity is required. When dimensioning the tank, the water used for irrigation and construction purposes was assumed to be constant and not increase with the increasing population. Although there are no indications currently that this will change, the lack of a proper land use plan means that an increased demand for water for irrigation and construction purposes cannot be excluded. This aggravates the process of dimensioning the size of the water storage tank. However, it is necessary to make assumptions when the future is unknown, and the assumptions that were made when considering the tank size are considered reasonable.

The water quality analysis that was performed on rainwater samples from the roofs was very limited, which creates an uncertainty regarding the water quality from the RWH. The water quality analysis was only performed on rainwater that was recently collected, meaning that how the quality of the water will be affected by storage in a concrete tank is unknown. Furthermore, the presence of any pollutants that are harmful to humans, animals, or the environment was not thoroughly investigated in the water quality analysis. Even though the water is not intended for any potable or hygiene usage, the people at the site will still be in contact with the water when using it for irrigation and construction. If the water contains harmful pollutants, there is therefore still a risk for spreading of diseases among the users. The fact that irrigation at the site is mostly performed by drip watering does, however, lower the risk of spreading of pollutants into the environment. The uncertainty of the water quality can also affect people's willingness to use the water. There is therefore a need for further investigations of the water quality once a RWH system has been constructed.

Although the implementation of a RWH system would lower the demand for municipal water for irrigation and construction work purposes, they do not affect the demand for other usage areas. Clean water is still needed for consumption, hygiene, cooking and washing, and as RWH do not produce water suitable for these activities, there is still going to be a large demand for municipal water. As the number of students and staff increases at the school, the demand for municipal water will further increase. There is therefore a need to investigate solutions that generate clean water that can safely be used for drinking and hygiene. Implementation of the proposed RWH system does, however, still lower the current need for municipal water. As the RWH system can cover the daily need of 975 lpd for irrigation for 70% of the year, approximately 249 000 L can be saved annually. This is equal to around 21 000 L per month, which represents nearly 20% of the monthly usage of municipal water for February to April. Using a RWH system can therefore significantly reduce the costs for water supply. However, it is important to note that the proposed RWH system almost exclusively supply the school with water during the rainy season. The problem with water accessibility during the dry season therefore remain, which is a major drawback of the proposed solution. Allocating construction work to the wet season is, however, one way to prolong the time for which the harvested rainwater can cover the water demand for irrigation during the dry season.

5.7 Greywater management

During field inspections of water management at the site, it was concluded that there is room for improvement as water is not always managed very efficiently. Greywater from showers, washbasins and laundering is currently discharged directly onto the ground without treatment or reuse. This practice not only wastes potentially useable water but also increases the risk of localised pollution. With simple measures, this greywater can be collected and treated for safe reuse in non-potable applications, which can improve the overall sustainability of the school's water management.

5.7.1 Possibilities of greywater reuse

As the only intended usage activities of reused greywater at the site were decided to be irrigation and construction, the proposed solutions aim to meet the quality requirements for water used for these purposes. Although water used for personal hygiene such as showering and washing hands was observed to be among the most water-demanding activity per day, the water used for laundry was considered the most suitable for treatment and reuse. The reason for this is that laundry water is already gathered in buckets, which makes it easy to pour the water into a treatment system without additional infrastructure. Reusing greywater from other sources where water exits the buildings at ground level means that the water must be either collected, transported and poured, or pumped to a higher elevated point since most of the greywater treatment methods are gravity-fed.

The greywater analysed from washing clothes by hand stood out as the most polluted water source in terms of pH, turbidity and conductivity among all the water samples that were collected and analysed at the site. Although greywater from other sources was not tested in this study, findings from similar contexts suggest that greywater from showers and sinks generally contains lower levels of pollutants than laundry water and is typically easier to treat (Rakesh et al., 2020). There is therefore potential for expanding the treatment to include greywater from these sources in the future, which could significantly increase the volumes of greywater available for reuse and further reduce the environmental impact of wastewater discharge at the site.

5.7.2 Proposed greywater solutions

To improve water reuse practices and reduce environmental contamination, two simple and low-cost greywater treatment methods are proposed. The first solution involves a gravity-based filter system using plastic barrels filled with gravel, sand, and activated charcoal. The design for the treatment is based on studies by Shaikh & Ahammed (2022) and Huhn et al. (2015). In this system, greywater is poured into the top of the barrel, flows downward through the filter layers, and exits via a tap at the bottom. The coarse gravel layer removes larger particles and debris, the fine sand filters suspended solids and reduces turbidity, and the top layer of charcoal absorbs odours, organic matter, and some chemical contaminants. The greywater solution is illustrated in Figure 5.11 which shows the order of the filtration layers in the barrel. The approximate thicknesses of the layers are 10 cm of activated charcoal, 50 cm of fine sand, and 20 cm of gravel.

Figure 5.11: Illustration of the greywater treatment barrel. The cross-section shows the gravel, sand, and activated charcoal layers. The design is based on Shaikh & Ahammed (2022) and Huhn et al. (2015).

This solution is well suited to the Tumaini Open School as it enables the school to treat the greywater to a certain extent. The possibility to reuse the treated greywater is a step towards the goal of reducing the school's reliance on the municipal water supply. However, even though this filtration would result in improved water quality compared to the current situation where no treatment is applied, it is important to note that it is not comparable to the treatment that can be performed at a wastewater treatment plant. Further water quality analyses should therefore be conducted to assess the water quality to determine which reuse purposes are suitable. If the analysis shows that the water is of insufficient quality for crop irrigation or construction work, it should continue to be used for bush irrigation, which is the current usage of greywater from laundry. Although not ideal, the filtration is still beneficial as it reduces the pollutants that are released into the environment when greywater is disposed.

Similar filtration systems have been successfully implemented in rural contexts. Samal et al. (2020) documented the effectiveness of layered gravel-sand-charcoal filters in reducing turbidity, suspended solids, and chemical oxygen demand to levels safe for non-potable uses. These systems require minimal maintenance, mainly occasional cleaning and periodic replacement of the charcoal. Furthermore, the filtration barrels do not rely on electricity or chemical additives. Further advantages include improved hygiene, reduced environmental pollution, and enhanced water availability for secondary uses, all while using locally available material and simple construction methods. The suggested solution is uncomplicated and easy to understand and use. Furthermore, it does not complicate the process of doing laundry, or other greywater generating activities, since the barrels can be placed in close vicinity to where these activities are performed. The proposed solution is a model that could be adopted by other schools and communities in similar rural settings. As the barrels are rather small, and the greywater production rather large, several filtration barrels are required at the site to make the solution effective. This increases the costs and resources needed for both installation and maintenance work. Many smaller greywater treatment stations in comparison to one larger do, however, facilitate the reuse possibilities in different areas on the site.

The other greywater treatment solution that could be implemented at the site is an elevated plant filtration bed, where untreated greywater is filtered through a container filled with soil and vegetation. As the water flows horizontally through the medium, pollutants are removed by a combination of physical, chemical, and biological processes. This method mimics constructed wetlands and can be used to treat greywater effectively for non-potable purposes such as irrigation and construction work. An illustration of the proposed treatment is shown in Figure 5.12 below. The plant bed system design is based on a study by Collivignarelli et al. (2020).

Figure 5.12: Design of the elevated plant filtration bed. The cross section shows the layers of gravel, soil and sand that greywater passes through, as well as the plant roots that treats the water through microbial degradation and plant uptake. The design is based on Collivignarelli et al. (2020).

The elevated plant filtration bed system has several potential advantages over filtration barrels. The larger surface area and biological treatment enabled by plant roots and soil microbes can result in a more efficient removal of nutrients, organic matter, and microorganisms in the greywater. In addition to improving water quality, these beds can contribute to biodiversity by providing habitats for various plants and microorganisms. They can also have aesthetic and educational value in a school environment where they can serve as a practical tool for teaching students about ecology, water treatment and sustainability. Because of their larger treatment capacity and passive operation, it means that elevated plant filtration beds require less frequent maintenance once they are constructed. However, regular checks are still necessary to prevent clogging or mosquito breeding due to poor drainage. Filtration beds also require pre-treatment through a mesh or sediment trap since it is important to prevent solids from accumulating in the bed. They must also be designed with adequate slope and drainage to ensure proper water flow and avoid water stagnation.

A benefit of elevated beds is that the treated water can be collected from a simple outlet pipe and directly used for nearby garden irrigation. The proximity to vegetable beds or green zones around the school can make reuse more convenient. In the long term, these systems are most likely more sustainable than smaller, more decentralised solutions since they require fewer repeated interventions and maintenance work. However, they require more initial effort and higher costs to construct, which makes them most suitable for locations where greywater reuse can be centralised, such as near laundry areas or student dormitories. Several studies have confirmed the long-term effectiveness of planted soil filtration beds in treating greywater. Sasse (1998) and Pinto et al. (2010) found in their studies that planted filtration beds can remove over 90% of suspended solids and significantly reduce faecal coliforms, as long as the treatment systems are not overloaded. The relatively low cost and lack of energy requirements for the system make them ideal for rural schools.

Rather than choosing between filtration barrels and elevated filtration beds, a combined solution that uses both methods in sequence is proposed. Greywater can first pass through the layered filtration barrels for primary treatment, which removes solids, odours, and suspended particles. The partially treated greywater can then be channelled into an elevated filtration bed for secondary treatment, which further removes nutrients and pathogens through soil filtration and plant uptake. This filtration system in sequence maximises treatment efficiency and increases the likelihood that the treated water will meet safe standards for a variety of reuse purposes. It can also provide flexibility, since filtration barrels can be used alone in areas close to greywater sources, while the full combined system can be applied in areas where space allows, and greywater can be collected and transported in bulk.

The integration of both systems supports a decentralised approach to water management. At smaller points of generation, such as laundry areas, filtration barrels provide immediate treatment and reuse. Meanwhile, the elevated filtration beds can serve as community treatment hubs, where larger volumes of greywater are processed for centralised reuse in irrigation or construction work. Just as with rainwater harvesting, greywater reuse contributes to sustainability in terms of social, economic, and environmental aspects. It provides an additional water source, reduces dependency on the unreliable municipal system, and minimises pollution. By treating and reusing greywater instead of discharging it untreated into the environment, the school can increase its water resilience and promote more sustainable water practices.

5.7.3 Discussion of solutions for greywater reuse

Much like the RWH solution, the greywater reuse at the site will only impact the water demand for irrigation and construction work. Although the proposed solutions will likely treat the water sufficiently for these purposes, more extensive treatment is required to achieve a sufficient water quality for hygiene or potable uses. With the estimated volumes of greywater generated from laundry being 3 lpcd, around 5 400 L is produced monthly. Reusing this greywater would reduce the monthly water demand with around 5%, based on the monthly water demand at the site from January to April 2025. Reusing greywater from additional sources like showering, hand washing, and washing dishes can further increase the potential of greywater reuse at the site. Implementing these greywater solutions in combination with the proposed RWH system could potentially reduce the water demand from the RWH tank and extend the time during which the demand for irrigation and construction work can be met by the harvested rainwater.

An aspect that should be investigated before implementing any greywater reuse at the site is the user acceptability of reusing the treated greywater. As previous studies show a low acceptability of reusing greywater for purposes that require a direct contact, there is a risk that the case would be the same at Tumaini Open School (Al-Khatib et al., 2022). The literature shows great variations in which reuse purposes are accepted by the users, but the general view is that purposes not requiring direct contact are preferred. Bautista Quispe et al. (2025) performed a study at a school in a similar setting as Tumaini Open School and found a high acceptance of greywater reuse for purposes like cleaning, irrigation, and toilet flushing among others. However, the acceptance rate is fluctuant and can differ between projects or the selection group being studied. This is highlighted by the fact that other studies have shown a low acceptability for reusing greywater for similar purposes (Al-Khatib et al., 2022; Bakare et al., 2016).

To investigate the acceptance rate by the students and staff at Tumaini Open School, a questionnaire about the willingness to reuse greywater for different purposes could be performed. A drawback of this would, however, be the uncertainty of the participants having enough knowledge about greywater or an unwillingness to provide honest answers. The willingness likely depends on the initial situation of water management. For example, the students at Tumaini Open School performs all their laundry by hand and therefore already have direct contact with greywater. What is uncertain is how they would react to being in contact with somebody else's greywater from for example washing clothes or showering. On one hand, the students have a very close relationship to each other as they live, study, work, and socialise together every day. On the other hand, there is still a difference in being in contact with your own greywater compared to somebody else's. Since the concern of health risks is one major threat for the willingness to reuse greywater, the importance of testing the quality of the greywater after treatment is once again stressed. The water quality analysis should be performed in a transparent way where the residents of the school should be informed of the results. This can hopefully increase the students' knowledge about greywater and support them in setting boundaries for which reuse purposes they are willing to accept.

5.8 Potential drilling of a borehole

Due to the presence of free roaming animals, graves and septic tanks at the site, in combination with the poor management of garbage and greywater there is a possibility of groundwater contamination at the site. Since the graves on the school area are relatively new, the contamination from these is expected to be relatively high. This is therefore something that needs to be considered, despite the local restrictions about the minimum distances from a borehole to contamination sources being fulfilled for the appointed location. Investigations of the topography of the site show that the appointed location of the borehole is lower elevated compared to the sources of contamination, which increases the risk for contamination. Due to the uncertainty of the groundwater quality of the site, it is currently not recommended to drill a borehole for extraction of groundwater, and more extensive investigations of groundwater quality are needed before deciding on the matter.

The extensive costs associated with the applications for and drilling of a borehole in Tanzania also indicate that there are other solutions to prioritise. A more sustainable management of garbage and greywater at the site should preferably be implemented before investing in the drilling of a borehole. The implementation of the RWH system and the greywater treatment are instead the proposed solutions as of now. The potential of drilling a borehole at the site is, however, something that could be investigated in future projects to further improve the water supply to the school and make it even more self-sufficient. For instance, there is a possibility that there might be a more suitable location on the school area for the drilling of a borehole. A major benefit that could be seen with extracting groundwater from a borehole is that it has potential to be used for hygiene or consumption, which is not currently recommended for the RWH or greywater solution proposed in this study.

5.9 Future areas of study

When performing the study at Tumaini Open School, several weak areas in need of improvement were detected. These could be considered when designing future projects at the site. One future area of study is to investigate the wastewater management at the site. Even though the greywater management was touched upon in this study, it could be researched further. This study focused on analysing water from washing clothes and finding a solution for managing it better. Future studies can develop the idea further, and include the greywater generated from showering, washing hands, and washing dishes. Blackwater management was not covered at all in this study and is therefore another topic to examine in future studies. The impact of the proximity of septic tanks to both residential areas, food producing crops, and a shallow water well, are areas that could be studied. Furthermore, the potential drilling of a borehole to extract groundwater at the site is a topic that is only briefly discussed in this thesis. The uncertainty of groundwater quality due to potential contamination from the lack of greywater management resulted in the potential borehole not being investigated further in this study. An in-depth study of it would, however, be interesting to perform, and if proven possible, a borehole would assist Tumaini Open School in their goal of reducing their reliance on municipal water. There is also a potential that groundwater extracted from a borehole at the site could be used for other purposes like hygiene or even drinking. This could be an interesting point to investigate since the suggested solutions in this study mainly focus on supporting the water supply for irrigation and construction work.

This study can serve as a basis for how to improve the water situation at the Tumaini Open School with regards to water supply, reuse and flood mitigation. No implementations of any solutions were carried out in this study, and therefore, there is a great uncertainty of when, or even if, these solutions will be implemented. There is also an uncertainty of what the genuine impact of the solutions will be, and to what extent they will be used. Future studies can utilise the material produced in this study to build and develop the proposed solutions at the site. Once implemented, the efficiency and usefulness of the solutions can be studied.

6 Conclusion

Harvesting rainwater from roof areas was identified as a well-suited solution to improve water availability on the site. The study recommends collecting rainwater from roofs and storing it in a 60 000 L partly underground concrete tank, which balances storage capacity and cost effectiveness. Although local rainfall patterns indicate that the system would be most effective during the rainy season, its implementation would still improve the water availability, and enhance the social, economic, and environmental sustainability at the site. Constructing swales along the sides of the roads were concluded to be the most effective solution to mitigate flood risks at the site. These can effectively minimise the soil erosion on the roads while also reducing pollutants in surface water. Two simple low-cost filtration methods, layered filtration barrels and elevated plant filtration beds, were proposed to treat greywater and reuse it for irrigation and construction purposes. These further reduces the demand on the municipal water supply network. All proposed solutions were adapted to locally available material and expertise to minimise costs and enhance long-term sustainability.

Although no solutions were implemented in this study, the findings provide valuable insights for future research. Future studies should focus on implementation and monitoring of long-term effectiveness of solutions once implemented. Examining the user acceptability and the water quality after greywater filtration or rainwater storage is needed before implementing the solutions to ensure suitability and safety for the intended usage areas. While the proposed solutions for rainwater harvesting and greywater reuse in this study can help reduce the water demand for irrigation and construction purposes, they do not address water needed for drinking, hygiene or cooking. Future studies should therefore expand their scope to also focus on water supply for these essential purposes. There is also a great potential for further studies of greywater use at the site, incorporating greywater from other sources than laundry. Despite lacking access to a laboratory during the field work, the findings of the study still contributed to an increased knowledge of the water-related challenges at the site. The information gathered provided a foundation for locally adapted implementations to improve water sustainability at Tumaini Open School but can also be used to address water-related issues at other sites with similar settings.

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A: Field measurements with handheld GPS

Appendix A presents detailed information of the collection of topographic data at the site with the help of a handheld GPS.

Table A.1: Information of recordings of elevation data collection. Includes date and time of sampling, as well as weather observation and other notes

Date	**Time**	**Weather condition**	**Notes**
2025-02-21	11.44	Clear sky	Land area calculation 1
2025-02-21	15.40	Partly clouded	To store along highway
2025-02-21	16.48	Partly clouded	RT1: Around school area, north
2025-02-22	11.14	Clear sky	RT2: Along highway, up and around mountain, rock industry
2025-02-23	12.34	Clear sky	RT3: Around school area, south
2025-02-23	17.34	Partly clouded	RT4: Isukamahela primary school, north of school and along highway
2024-02-24	15.05	Clear sky	Land area calculation 2
2024-02-26	18.15	Clear sky	To and along highway
2025-03-03	15.25	Partly clouded	RT6: Around school area
2025-03-06	16.38	Clear sky	RT7: Isukamahela primary school, west and south of school
2025-03-07	17.35	Clear sky	RT8: Up on the nearby mountain, to the top
2025-03-13	17.24	Partly clouded	Around the school area, north
2025-03-13	18.06	Partly clouded	Around the school area, south
2025-03-17	10.09	Partly clouded	Land area calculation 3
2025-03-19	08.32	Clear sky	Smaller roads outside of school area
2025-03-21	17.02	Clouded	North of the school area
2025-03-27	15.35	Partly clouded	Around grass area northeast of the school. Main road east and up to limit of the mountain
2025-03-31	18.07	Clear sky	Around grass area northeast of the school. More detailed measurements in the cultivated land around living area for students
2025-04-14	12.19	Partly clouded	Road south of school area and along road crossing the school area
2025-04-15	07.14	Clear sky	Roads east and north of school area. Along road crossing the school area
2025-04-16	11.52	Clear sky	Along the road crossing the school area, the northern land area of the school
2025-04-16	15.24	Partly clouded	Northern and southern part of the school area
2025-04-18	07.30	Clear sky	On the roads around the school to the north, south, east, and west

2025-04-20	18.14	Clear sky	On the roads around the school to the northeast and southwest

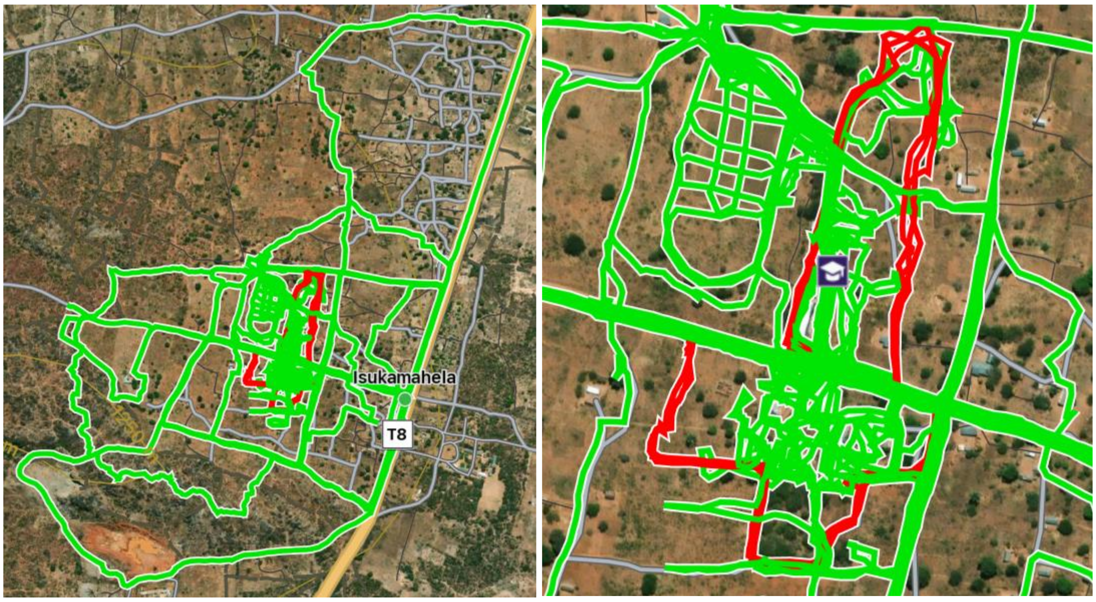


Figure A.1: a) Overviewing map showing the areas where GPS data has been collected. The green lines show all the places where tracks have been recorded, in proportion to the school area which is shown in red. b) A zoomed in overview of the GPS data collection coverage in the school area.

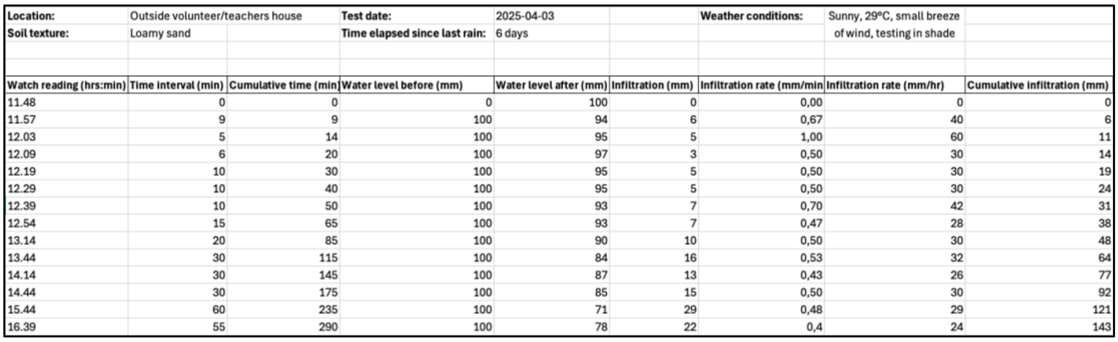
Table A.2: Recording of sampling of land area including time and date of sampling as well as present weather conditions at the time.

Sample	Date	Time	Weather condition
1	2025-02-21	11.44	Clear sky
2	2025-02-24	15.05	Clear sky
3	2025-03-17	10.09	Partly clouded

B: Soil infiltration test

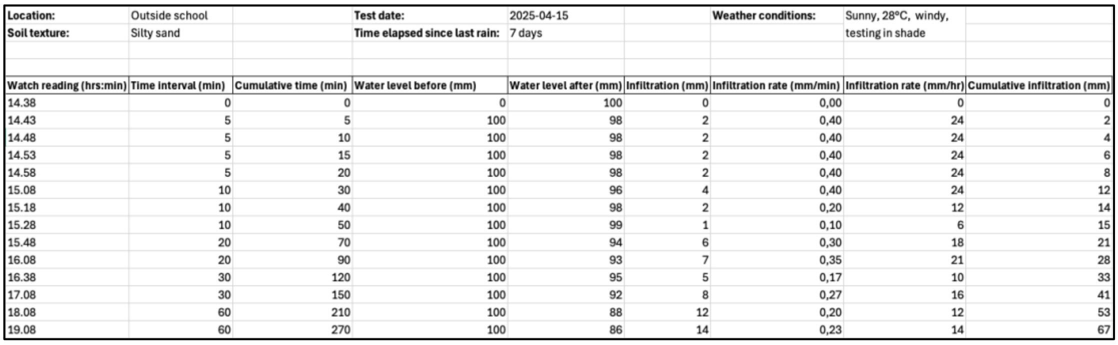
Appendix B presents the protocol of the soil infiltration test. A final infiltration rate of the soil was calculated based on this data.

Table B.1: Recordings of the first soil infiltration test outside the living area for students and volunteers. Includes the time, location, and weather conditions while sampling as well as time intervals and infiltration of water into the soil.



Location:	Outside volunteer/teachers house		**Test date:**	2025-04-03		**Weather conditions:**	Sunny, 29°C, small breeze	
Soil texture:	Loamy sand		**Time elapsed since last rain:**	6 days			of wind, testing in shade	
Watch reading (hrs:min)	**Time interval (min)**	**Cumulative time (min**	**Water level before (mm)**	**Water level after (mm)**	**Infiltration (mm)**	**Infiltration rate (mm/min**	**Infiltration rate (mm/hr)**	**Cumulative infiltration (mm)**
11.48	0	0	0	100	0	0,00	0	0
11.57	9	9	100	94	6	0,67	40	6
12.03	5	14	100	95	5	1,00	60	11
12.09	6	20	100	97	3	0,50	30	14
12.19	10	30	100	95	5	0,50	30	19
12.29	10	40	100	95	5	0,50	30	24
12.39	10	50	100	93	7	0,70	42	31
12.54	15	65	100	93	7	0,47	28	38
13.14	20	85	100	90	10	0,50	30	48
13.44	30	115	100	84	16	0,53	32	64
14.14	30	145	100	87	13	0,43	26	77
14.44	30	175	100	85	15	0,50	30	92
15.44	60	235	100	71	29	0,48	29	121
16.39	55	290	100	78	22	0,4	24	143

Table B.2: Recordings of the second soil infiltration test outside the school building. Includes the time, location, and weather conditions while sampling as well as time intervals and infiltration of water into the soil.



Location:	Outside school		**Test date:**	2025-04-15		**Weather conditions:**	Sunny, 28°C, windy,	
Soil texture:	Silty sand		**Time elapsed since last rain:**	7 days			testing in shade	
Watch reading (hrs:min)	**Time interval (min)**	**Cumulative time (min)**	**Water level before (mm)**	**Water level after (mm)**	**Infiltration (mm)**	**Infiltration rate (mm/min)**	**Infiltration rate (mm/hr)**	**Cumulative infiltration (mm)**
14.38	0	0	0	100	0	0,00	0	0
14.43	5	5	100	98	2	0,40	24	2
14.48	5	10	100	98	2	0,40	24	4
14.53	5	15	100	98	2	0,40	24	6
14.58	5	20	100	98	2	0,40	24	8
15.08	10	30	100	96	4	0,40	24	12
15.18	10	40	100	98	2	0,20	12	14
15.28	10	50	100	99	1	0,10	6	15
15.48	20	70	100	94	6	0,30	18	21
16.08	20	90	100	93	7	0,35	21	28
16.38	30	120	100	95	5	0,17	10	33
17.08	30	150	100	92	8	0,27	16	41
18.08	60	210	100	88	12	0,20	12	53
19.08	60	270	100	86	14	0,23	14	67

C: DEM improvement through GPS data collection

Appendix C show the improvement in data resolution of the DEM at the site after collected GPS data had been merged with open-source data.

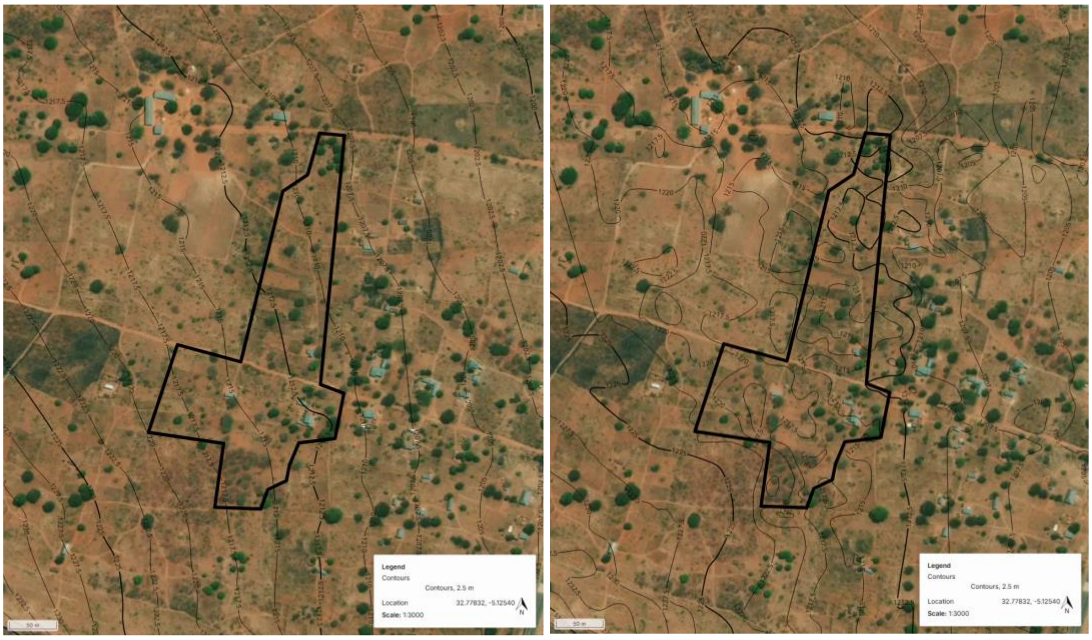


Figure C.1: Contour lines showing the elevation at Tumaini Open School. a) DEM before GPS data collection. b) Improved DEM after GPS data collection.

D: Field observations after rainfall during night

In Appendix D more detailed descriptions of field observations related to floodings are showed. These were used as a complementation to the flood simulations performed at the site, to further improve the site assessment.

Table D.1: Measurement of rain volumes acquired from rain activities during night, and field observations of the consequences present afterwards.

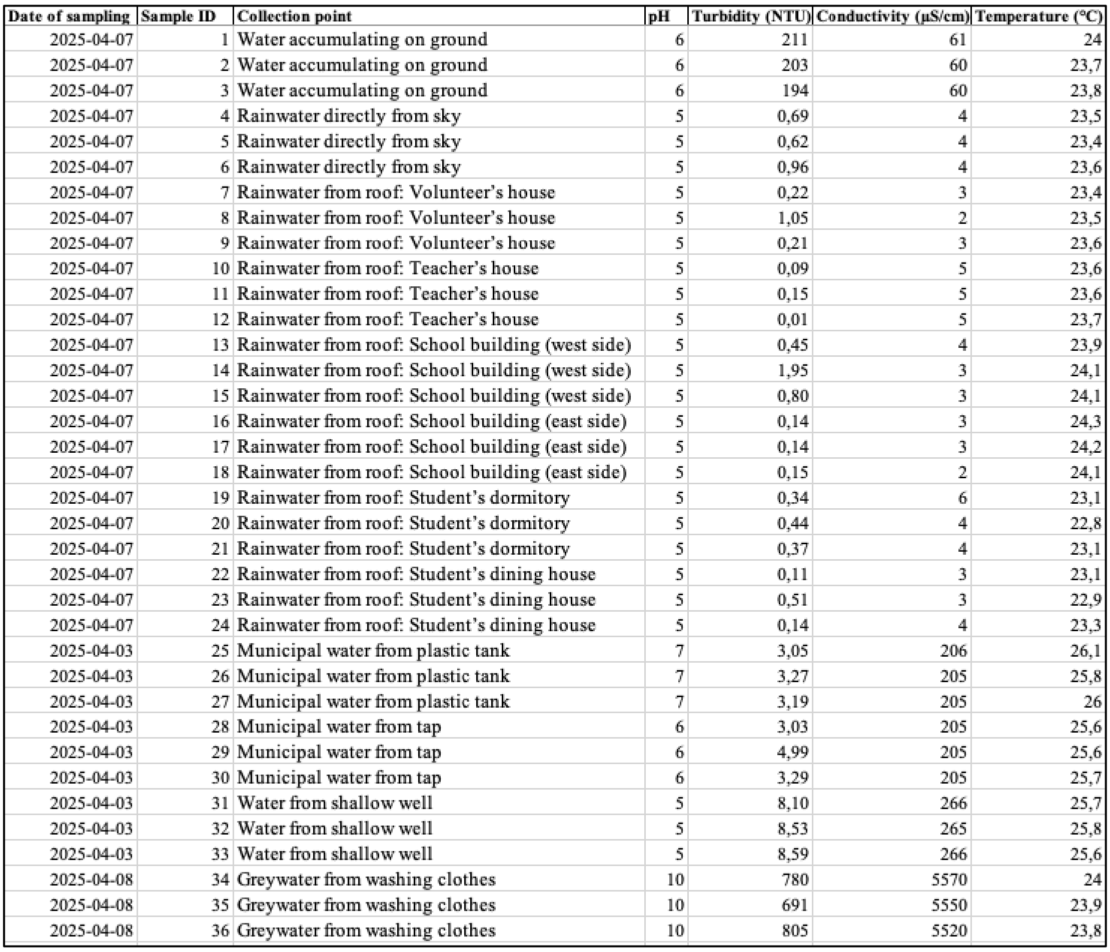
Time of water collection	**Collected volume of water (ml)**	**Total rain volume (mm)**	**Time of rain collection (hours)**	**Consequences**
2025-03-26 22.00 to 2025-03-27 08.00 (Most previous rain activity on the night before)	500 (Flask was placed on a wooden plank on the ground when measuring the rain intensity. There was a little bit of sand in the flask in the morning, possible that water also splashed into the flask.)	78	10 (Did not rain constantly during the night, very heavy precipitations around 03, 04, 06. No rain activity when going to sleep at 22. Light rain after 08, stopped at 09.30.)	9.40: Puddles of rain in multiple places. More and larger puddles in and right outside living area for volunteers/teachers. Some puddles present in school area or construction site. Soil erosion from the rain occurring on main road. 11.40: Smaller puddles, no standing water but still wet areas. Large puddles down by volunteers/teachers living area plus at construction site still filled. 16.00: Almost all puddles gone. Only the one by the construction site and the two by volunteer/teacher's house were left. The one inside the gates was almost gone and the one just outside still filled.
2025-03-27 22.00 to 2025-03-28 08.00	18 (No sand in the flask. Flask on a	3	10 (Not constant rainfall, light to intermediate rain	The puddle from yesterday outside the residential area for volunteers and teachers was still

(Most previous rain activity on the night before)	upside down turned bucket, approximately 50 cm over ground)		activities observed at 04. No rain at 22 or 06, but light/intermediate rain from 06.15 to 07.30) Rain continued at 09.15 to around 13.00.	present when the day ended (before this nights rainfall) Rain returned during the day. Not as intense rain as the previous night. Puddles in the same places, although not as distinct as it was wet everywhere. Since it was raining on and off up until the afternoon, and some water accumulation was still present from the rain the night before, there were wet spots that remained for most of the day
2025-04-06 22.00 to 2025-04-07 07.00 (Most previous rain activity 3,5 days before)	450 (No sand in the flask. Flask on a upside down turned bucket, approximately 50 cm over ground)	71	10 (There were periods of heavier rain and periods of lighter rain. No information on if the rain stopped for some periods. Still raining in the morning up until around 07.30.)	07.00: Streams of water flowing along the road during and right after rainfall. Soil very soft and almost like quicksand. 10.30: Water had runoff or infiltrated into the soil in most areas. Puddles remaining in residential area for teachers and volunteers and construction site. 15.00: Rain continuing during the day on a light/moderate scale, with some heavy rain showers. Flow of water along the road crossing the schools land which caused soil erosion.

E: Analysis of water samples

Appendix E presents the raw data from the water quality analysis before it was compiled.

Table E.1: Recordings of the measured pH, turbidity, conductivity, and temperature from each sample collected.



Date of sampling	Sample ID	Collection point	pH	Turbidity (NTU)	Conductivity (µS/cm)	Temperature (°C)
2025-04-07	1	Water accumulating on ground	6	211	61	24
2025-04-07	2	Water accumulating on ground	6	203	60	23,7
2025-04-07	3	Water accumulating on ground	6	194	60	23,8
2025-04-07	4	Rainwater directly from sky	5	0,69	4	23,5
2025-04-07	5	Rainwater directly from sky	5	0,62	4	23,4
2025-04-07	6	Rainwater directly from sky	5	0,96	4	23,6
2025-04-07	7	Rainwater from roof: Volunteer's house	5	0,22	3	23,4
2025-04-07	8	Rainwater from roof: Volunteer's house	5	1,05	2	23,5
2025-04-07	9	Rainwater from roof: Volunteer's house	5	0,21	3	23,6
2025-04-07	10	Rainwater from roof: Teacher's house	5	0,09	5	23,6
2025-04-07	11	Rainwater from roof: Teacher's house	5	0,15	5	23,6
2025-04-07	12	Rainwater from roof: Teacher's house	5	0,01	5	23,7
2025-04-07	13	Rainwater from roof: School building (west side)	5	0,45	4	23,9
2025-04-07	14	Rainwater from roof: School building (west side)	5	1,95	3	24,1
2025-04-07	15	Rainwater from roof: School building (west side)	5	0,80	3	24,1
2025-04-07	16	Rainwater from roof: School building (east side)	5	0,14	3	24,3
2025-04-07	17	Rainwater from roof: School building (east side)	5	0,14	3	24,2
2025-04-07	18	Rainwater from roof: School building (east side)	5	0,15	2	24,1
2025-04-07	19	Rainwater from roof: Student's dormitory	5	0,34	6	23,1
2025-04-07	20	Rainwater from roof: Student's dormitory	5	0,44	4	22,8
2025-04-07	21	Rainwater from roof: Student's dormitory	5	0,37	4	23,1
2025-04-07	22	Rainwater from roof: Student's dining house	5	0,11	3	23,1
2025-04-07	23	Rainwater from roof: Student's dining house	5	0,51	3	22,9
2025-04-07	24	Rainwater from roof: Student's dining house	5	0,14	4	23,3
2025-04-03	25	Municipal water from plastic tank	7	3,05	206	26,1
2025-04-03	26	Municipal water from plastic tank	7	3,27	205	25,8
2025-04-03	27	Municipal water from plastic tank	7	3,19	205	26
2025-04-03	28	Municipal water from tap	6	3,03	205	25,6
2025-04-03	29	Municipal water from tap	6	4,99	205	25,6
2025-04-03	30	Municipal water from tap	6	3,29	205	25,7
2025-04-03	31	Water from shallow well	5	8,10	266	25,7
2025-04-03	32	Water from shallow well	5	8,53	265	25,8
2025-04-03	33	Water from shallow well	5	8,59	266	25,6
2025-04-08	34	Greywater from washing clothes	10	780	5570	24
2025-04-08	35	Greywater from washing clothes	10	691	5550	23,9
2025-04-08	36	Greywater from washing clothes	10	805	5520	23,8

F: Alternative design of RWH solution

Appendix F show the design of an alternative RWH that potentially could be implemented at the site. This solution is however not the final recommendation.

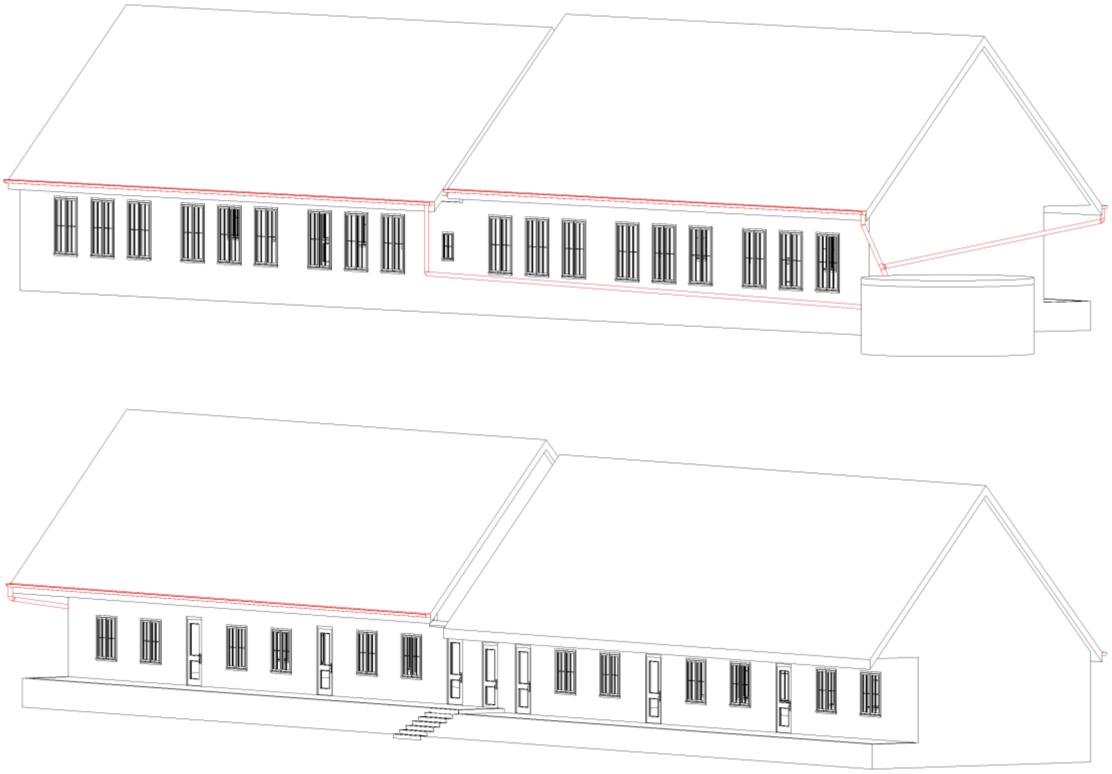


Figure F.1: Design of RWH solution if the water storage tank is placed in the south end of the school. Only three out of four roofs are available as collection areas for harvesting rainwater.

G: Dimensioning of water storage tank

Appendix G shows material used when dimensioning the water storage tank for the RWH system.

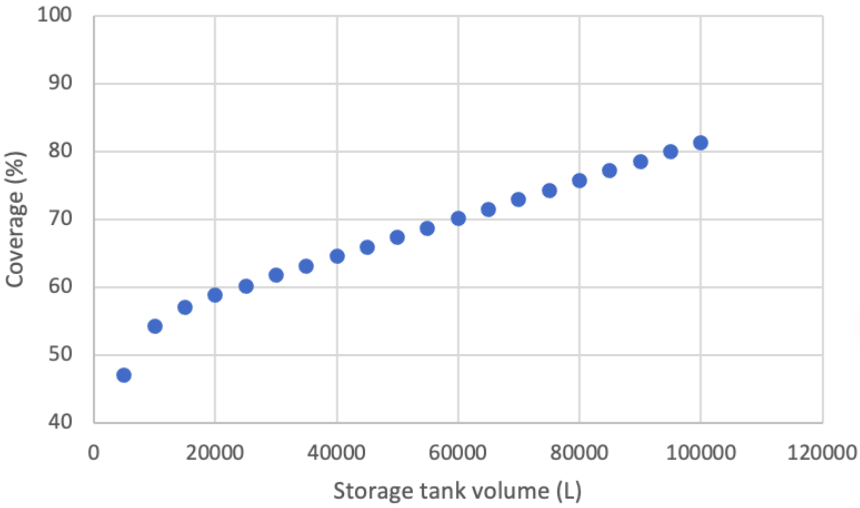


Figure G.1: Relationship between the storage tank volume and the coverage rate of the water demand throughout a year.

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