Master's thesis

NTNU
Norwegian University of Science and Technology
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Performance evaluation of a combined stormwater detention and reuse system

A case study from Trondheim, Norway

Master's thesis in Civil and Environmental Engineering
Supervisor: Tone Merete Muthanna
Co-supervisor: Knut Alfredsen
June 2021

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Kunnskap for en bedre verden

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Preface

This master's thesis was written during the spring semester of 2021. It is submitted to the Department of Civil and Environmental Engineering at the Norwegian University of Science and Technology (NTNU). It counts for 30 credits under the subject code TVM4905 Water and Wastewater Engineering.

The topic is stormwater management and stormwater reuse, and the thesis focus on a pilot stormwater management system located in Trondheim, Norway. A specialization project has been carried out as a pre-study prior to this master's thesis (Kjellsen, 2020). A part of the theoretical background presented in this master's thesis was developed in the pre-study. The project is carried out in cooperation with the research centre Klima 2050.

I especially thank my supervisors Tone Merete Muthanna and Knut Alfredsen for guidence and help with the thesis.

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Eirik Kjellsen

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Abstract

Urban stormwater systems typically experience multiple challenges because of urbanization and climate change, such as higher runoff volumes and peak flow. In addition, potable water is limited in many areas around the globe. In later years, stormwater reuse has gained popularity in urban areas to enable the use of stormwater for typically non-potable water uses. In this context, a pilot stormwater management system has been constructed at the Zero Emission Building (ZEB) site at Gløshaugen in Trondheim, Norway. The ZEB-pilot combines bioretention cells and a permeable pavement with an underground stormwater tank. This tank has the possibility for multiple-use, with an active volume for reuse as well as a detention volume for larger storm events. This master's thesis evaluate the performance of the ZEB stormwater management system related to stormwater control and discuss reuse opportunities for the system. To accomplish this, performance data is collected, and the system is modeled.

The water level in the tank is monitored to evaluate the stormwater detention performance. The monitoring and observations revealed leakage from the tank, as well as a misconfiguration of the outlet. This shortened the period with correct data to analyse.

To model the stormwater system, a two-step model is created. A rainfall-runoff module developed in U.S. EPA SWMM (Environmental Protection Agency Storm Water Management Model) simulates the process from rainfall to tank inflow. In this module, the catchment is created, and the bioretention cells and permeable pavement are included. Further, a behaviour storage module based on the level-pool routing method simulate the water balance in the tank. This module handles both orifice outflow and demand.

Simulations are carried out both on design events and long-term historical data to analyse the stormwater control potential of the system. Results indicate that the system is predicted to perform well within the design expectations by effectively providing detention for high precipitation events.

The active volume available for reuse is at this point not utilized, as equipment such as pumps and pipes is not installed in the tank. Simulations are therefore carried out to find the reuse potential of the system. Variability in rainfall is found as a defining factor limiting the amount of water that can be covered at all times. However, if accepted that water will not be available at all times, results indicate the tank can provide 2000 l/day with above 70% coverage. Irrigation and bike washing are identified as the most likely implementations. Even so, the seasonal variations of these purposes may limit the effectiveness of such implementations. Toilet flushing is a large non-potable consumption in office/education buildings. The ZEB laboratory is roughly estimated to require 1400 l for toilet flushing on workdays. Simulations indicate that the tank can cover 90% of the toilet flushing in the ZEB laboratory. However, the implementation of reuse water for toilet flushing may require expensive installations. Stakeholders must eventually decide what reuse purposes to implement at the ZEB laboratory site.

Sammendrag

Urbanisering og klimaendringer forårsaker utfordringer med overvann slik som høyere avrenningingsvolum og avrenningstopp. Ferskvann er i tillegg en begrenset ressurs mange steder på kloden. Derfor har det i urbane strøk de siste årene blitt ett fokus på gjenbruk av overvann til bruksområder som typisk ikke krever drikkevannskvalitet. På tomten til ZEB (Zero Emission Building) - laboratoriet, på Gløshaugen i Trondheim, har det blitt etablert ett pilot overvannssystem. Dette systemet kombinerer regnbed og permeable dekker med en overvannstank. Denne tanken har ett aktivt volum ment for gjenbruk, samt ett fordrøyningsvolum for å forsinke overvannet. Denne masteroppgaven evaluerer systemet relatert til overvannskontroll og diskuterer systemets muligheter i forhold til gjenbruk av overvann. For å gjennomføre dette blir systemet overvåket og modellert.

Vannnivået i tanken er overvåket for å evaluere systemets overvannskontroll. Denne overvåkningen avslørte at det er lekkasje fra tanken. I tillegg avslørte målingene, sammen med observasjoner, at utløpet i tanken ikke var riktig satt opp under konstruksjon. Dette begrenset analyseperioden på systemet.

For å modellere systemet er det laget en to-steg modell. Det første steget er en modul i U.S. EPA SWMM (Environmental Protection Agency Storm Water Management Model) som simulerer prosessen fra regn til vann inn til tanken. Denne modulen inkluderer blant annet regnbedene og det permeable dekket. Videre er det laget ett Python-script til å simulere vannbalansen i tanken. Dette er basert på prinsippene bak level-pool routing metoden og er laget slik at den håndterer både begrensende utløp og trekk til forbruk.

Simuleringer er gjennomført for å evaluere systemet på overvannskontroll både på kunstig genererte regnskyll og på historisk nedbørsdata. Resultatene indikerer at systemet vil prestere godt innenfor forventningene satt i prosjekteringsprosessen.

Det aktive volumet i tanken er på dette tidspunktet ikke tatt i bruk, ettersom utstyr som pumper og rør til dette ikke er installert. Derfor er det gjennomført simuleringer for å finne gjenbrukskapasiteten til systemet. Perioder med lite nedbør begrenser mengden vann som alltid vil være tilgjengelig for gjenbruk. Likevel, hvis det aksepteres at mengden vann ikke vil være tilgjengelig til enhver tid, kan tanken levere 2000 l/dag med over 70% dekning. Vanning og vann til sykkelvask ser ut som de mest sannsynlige bruksområdene for det aktive volumet. Disse forbruksområdene er imidlertidig svært variable og årstidsavhengig, noe som kan begrense effektiviteten. Toalett spyling er normalt en stor andel av vannforbruket i kontor/undervisnings bygninger. Simuleringer indikerer at tanken kan levere vann til toalettspyling med 90% dekning. Likevel, implementering av tankvann til toalettspyling vil sannsynligvis innebære en betydelig innstalleringskostnad. Hvilke gjenbruksformål som skal benyttes for systemet må til slutt bestemmes av personer tilknyttet ZEB-laboratoriet.

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List of Abbreviations

CMAC - Continuous Monitoring and Adaptive Control

CSO - Combined Sewer Overflow

IDF - Intensity-Duration-Frequency

IoT - Internet of Things

LID - Low Impact Development

LOD - Lokal Overvanns Disponering (local handling of stormwater)

NSE - Nash–Sutcliffe model efficiency coefficient

RTC - Real Time Control

RWH - Rainwater Harvesting

SWH - Stormwater Harvesting

SWMM - Storm Water Management Model

TSS - Total Suspended Solids

YAS - Yield After Spillage

YBS - Yield Before Spillage

ZEB - Zero Emission Building

1 Introduction

1.1 Background

Urbanization, combined with climate change, creates challenges for urban stormwater systems all over the world. With urbanization, there has been an increase in impervious areas, which create changes in the natural water cycle (Shuster et al., 2005). When added together with the changing climate, which gives more intense precipitation events (Sorteberg et al., 2018), we see increases in peak flows, reduced times of concentration, reduced infiltration, and reduced groundwater recharge. With conventional stormwater systems, the stormwater is typically discharged as quickly as possible with a piped system. However, with changes in the water balance and more intense precipitation events, the capacity is often exceeded and causes issues such as increased flood risk and more frequent combined sewer overflows (CSOs) (Burns et al., 2012; Liu et al., 2014). Urbanization not only affects the quantity and timing of flows but also impacts water quality. Urban runoff increases the transport of pollutants and nutrients, leading to reduced water quality and the ecological degradation of many urban streams (Walsh et al., 2005). As a result, the management of urban stormwater systems has seen a significant change over the past few decades. Multiple objectives are now considered and included in the decision process. More distributed solutions are being applied, including retention and infiltration systems in which stormwater is viewed as a resource to be infiltrated, stored, and/or reused at the site (Fletcher et al., 2015; Hamel & Fletcher, 2014).

A wide range of stormwater control measures exists to control the quantity and remove pollutants from urban runoff. One popular measure is stormwater tanks, which store water before releasing it to the network in a controlled manner. The use of stormwater tanks can reduce downstream flooding and erosion by reducing the peak discharge and delaying the time to peak (Burns et al., 2015; Park et al., 2012). In later years, low impact development (LID) has emerged as a popular stormwater management philosophy. LID aims to return more to the natural water cycle by creating hydrological conditions closer to pre-development (Eckart et al., 2017). One LID measure is bioretention cells, also referred to as raingardens. A bioretention cell is a lowered area where the soil is layered to filter pollution and to reduce peak flow locally at the source. Bioretention has become one of the most frequently used stormwater management practices for urban environments (Davis et al., 2009; Kratky et al., 2017).

In Norway, the implementation of LOD, which can be translated to local handling of stormwater, is recommended as a step in handling stormwater (Miljø blad, 2018). A report from the national water association Norsk Vann recommends stormwater management in relation to the use of a three-step strategy. Step 1 of this strategy includes natural infiltration of smaller rainfall intensities, step 2 includes detention and regulation of larger rainfall intensities, while step 3 includes safe diversion on the surface with the use of secured flood paths (Lindholm et al., 2008).

The water supply systems are also experiencing unprecedented changes due to urbanization and climate change, as well as population growth. While urbanization and population growth increase water demand, climate change will most likely reduce the amount of water available (Hoekstra et al., 2018; Vörösmarty et al., 2000). With many regions across the world having limited access to a sufficient amount of water, there is an increasing interest in the reuse of stormwater (Amos et al., 2016). Reuse of stormwater is an ancient practice to cope with water supply needs. In urban areas it consists of the collection, storage, and possibly treatment of rainwater for multiple non-potable purposes. Although stormwater reuse primarily has been applied for water supply purposes, the possibility to combine reuse with stormwater management is creating interest also in more humid regions (DeBusk et al., 2013).

1.2 Thesis description and objectives

The Zero Emission Building (ZEB) pilot at Gløshaugen (Trondheim, Norway) is a living lab pilot for research on building materials, energy flow, and stormwater management systems. The ZEB laboratory opened in the fall of 2020 and is a pilot project for the research centre Klima 2050. The building will be a living laboratory, an office, and an education building in full operation where new solutions simultaneously can be developed and tested. The ZEB-pilot has a stormwater management system combining bioretention cells and a permeable pavement with an underground stormwater tank. Water from the ZEB-laboratory roof, a nearby parking lot and drain pipes on site will reach the tank. In the tank, there is an active volume for reuse as well as a detention volume for larger storm events. This is the first of its kind installed in Norway. As the system is newly installed, the performance has not previously been investigated. In addition, reuse of the active volume has not yet been implemented.

The main objectives of this master's thesis are to evaluate the performance of the ZEB stormwater management system for stormwater control, model the system for design considerations and requirements, and evaluate the reuse possibilities for the system. The water level in the stormwater tank is monitored for a time period of about six months. For further analysis, a two-step model is created. This model consists of a stormwater management model (SWMM) to simulate the processes that generate inflow to the tank and a Python-script to model the tank water balance.

Based on these objectives, this thesis addresses the following research questions:

- How did the ZEB stormwater management system perform during the monitoring period?
- What is the systems stormwater detention potential?
- What are the reuse possibilities for the system, and to what degree can water demand be met?

The structure of the thesis is the following. Initially, a literature review establishes the theoretical background needed to study the stormwater system as well as the theory regarding modeling. Then, the system with its connected catchment is presented and described. Further, the methods used in monitoring, analysing, and modeling are described. Finally, results are presented and discussed, before the thesis ends with a conclusion and remarks on further work.

2 Theory

The ZEB stormwater management system combines bioretention cells with a stormwater tank that has the possibility for reuse. The following chapter includes a literature review on bioretention, stormwater tanks and stormwater reuse systems, as well as descriptions about stormwater modeling approaches.

2.1 Bioretention

Bioretention cells, often referred to as biofilters or raingardens, are defined as a lowered area that consists of a surface ponding layer, vegetation, soil layer, storage layer, and a structure to handle overflow. The cell can be constructed with or without an underdrain (Liu et al., 2014). Bioretention has become one of the most frequently used stormwater management practices for urban environments (Davis et al., 2009). Figure 1 show an illustration of a bioretention cell. The media should be a mixture of high-permeability soil and organic matter to maximize infiltration and vegetative growth. The areas are planted with pollution- and water-tolerant trees, shrubs, and other species that promote evapotranspiration. The cell aims to both reduce the peak flow and improve the stormwater quality (Liu et al., 2014).

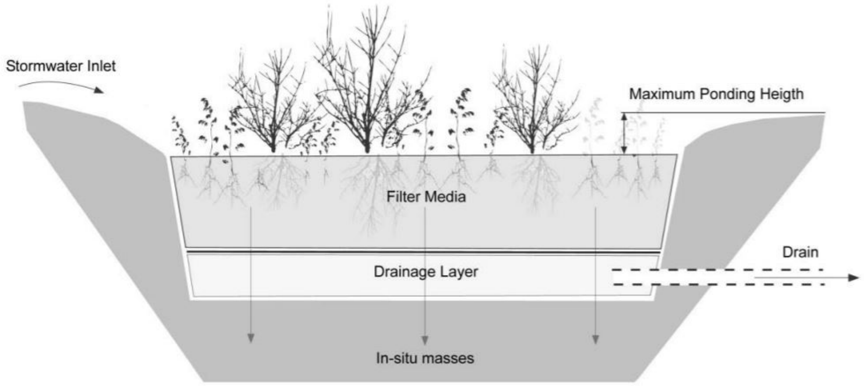


Figure 1: Illustration of a bioretention cell. Ponding occur if rainfall exceeds infiltration capacity. Overflow occur if maximum ponding height is exceeded. Media promotes infiltration, vegetation promotes evapotranspiration. Drain pipe is optional based on existing soil infiltration capacity. Source: B. C. Braskerud et al. (2013)

2.1.1 Hydraulic performance

The bioretention cell aims to reduce the peak flow and runoff volume by delaying runoff and promote both infiltration and evapotranspiration. Incoming runoff infiltrates through the media and is either infiltrated to native soil or discharged via the underdrain pipe (Liu et al., 2014). Bioretention media-saturated hydraulic conductivity (K_{sat}) is a measure of the hydraulic capacity of the cell. This parameter affects the cells ability to remove water during events and to remove surface water before the next event (B. Braskerud & Paus, 2014). The underdrain is needed if the existing/underlying soil has low permeability. Overflow may occur when the media in the cell is fully saturated. The cell is typically constructed with a ponding height of 15-30 cm. Hence, peak flow reduction is achieved by forming ponding water on the surface, retaining water within the media, and releasing it slowly via the piped underdrain (Kratky et al., 2017; Liu et al., 2014).

The cell reduces runoff volume via exfiltration to existing soil and with evapotranspiration. The cells ponding height and the medias porosity store water, which is then available for evapotranspiration or exfiltration (He & Davis, 2011). Evapotranspiration is the combination of transpiration and evaporation and will vary between cells based on climate and weather, but also vegetation and soil type. Exfiltration is influenced by the cells surrounding soils texture. If the native soils have good permeability, less runoff will be discharged from the underdrain (Kratky et al., 2017). Volume reduction does not only depend on the design of the system but also rainfall intensity. Events with a long return period will often result in overflow and, therefore, less bioretention capture. Bioretention volume reduction therefore depend on both hydrological conditions and hydraulic performance (Kratky et al., 2017; Trowsdale & Simcock, 2011).

The main challenge related to long-term hydraulic performance for a bioretention cell is reduced hydraulic conductivity due to compaction and clogging in the media. The vegetation is defined as a key in maintaining the soil structure and the infiltration (Kratky et al., 2017; Skorobogatov et al., 2020).

2.1.2 Stormwater treatment

Stormwater typically contains a large range of pollutants such as nutrients, metals, and organic compounds, and will often have large variations in both quantity and quality (Le Fevre et al., 2015). The bioretention cell performs the treatment by a variety of unit processes that make use of the chemical, biological, and physical properties of plants, microbes, and soils to remove pollutants from urban runoff (Liu et al., 2014). Bioretention systems will receive different pollutant loads based on their location and will need to be adapted according to the individual treatment goals (Roy-Poirier et al., 2010).

The bioretention cell reduces total suspended solids (TSS) by filtration and sedimentation. The removal of TSS in bioretention has been shown to be effective. In some new cells, it is reported that the cell leak TSS, but this appears to be an initial washout. Although TSS can be removed efficiently in the cell, it is also one of the leading factors causing reduced hydraulic conductivity through blockage of finer pores (Kratky et al., 2017; Liu et al., 2014). Urban areas commonly contribute with heavy metals such as copper (Cu), zinc (Zn), cadmium (Cd), and lead (Pb). Roads are one of the main sources contributing to heavy metal pollution. Heavy metals can typically be removed in a bioretention cell through interception by the surface media, physical adsorption onto the media, and plant absorption (Roy-Poirier et al., 2010). Multiple studies have shown examples of great removal efficiencies (Davis et al., 2009; Roy-Poirier et al., 2010). Davis et al. (2009) concludes that the removal mainly occurs in the upper layers of the cell. The particulate metals is removed primarily by filtration, while the dissolved are removed by adsorption. Removal of nutrients, nitrogen, and phosphorus is typically variable. Some cases have experienced good removal efficiencies, while others low. The removal depends heavily on media composition and design (Davis et al., 2009; Kratky et al., 2017).

2.1.3 Bioretention in cold climates

When designing bioretention for cold climates, there is a contradiction between designing for water quality improvement and stormwater quantity. With coarser media, water quality improvement may be limited and by using fine media to improve contaminant removal, concrete frost could form and the system's hydraulic performance would be inadequate. The spring runoff will typically give heavy loadings of sediments and heavy metals as the snow acts as a storage during winter. In addition, the impact road-salt has on contaminant removal and vegetation are not well understood, especially under long-term applications (Kratky et al., 2017). Paus et al. (2016) found that for cold climate bioretention cells the Ksat value should be above 10 cm/h to increase hydraulic performance.

2.2 Stormwater tanks

Stormwater tanks are usually underground storage constructions that mainly store stormwater, reduce the magnitude of peak flows and provide water quality treatment primarily through sedimentation. It can be multiple distributed tanks or a few central and larger structures. The excess stormwater can be stored safely until the rain event is over, where it typically can be discharged on to the municipal stormwater network in a controlled manner. The use of rainwater tanks has the potential to simultaneously address several social, economic, and environmental problems. The risk of urban flooding and CSOs can be reduced. Expensive modifications on the piped network may therefore be cancelled or delayed (Burns et al., 2015). The impacts of urbanization on the streams can be mitigated. With the urban stormwater led directly to the stream with conventional drainage systems, the stream can be severely degraded with respect to ecological health. This is a result of both the changed flow regime and reduced water quality (Burns et al., 2015; Walsh et al., 2005). The stormwater tanks also represent a potential for reuse. As presented in the next section (2.3), stormwater tanks can be applied for the reuse of stormwater for a wide range of purposes (Campisano, Butler, et al., 2017)

Despite these possibilities, the capacity of stormwater tanks is normally not fully utilised for a storm event. Real-time control (RTC) by controlling the tanks as systems during a storm represents a potential solution to mitigating urban flooding and CSOs. RTC will improve the systems adaptability to changes and future legal requirements (Beeneken et al., 2013; Liang et al., 2019). RTC requires the implementation of various hardware elements in the network, such as sensors, actuators, controllers, and data transmission systems. A stormwater tank is controlled in real-time if process variables are monitored and used to continuously operate actuators during an event (Schütze et al., 2003).

2.3 Stormwater reuse

2.3.1 Description and degree of implementation

Reuse of stormwater is an ancient practice to cope with water supply needs traditionally implemented in areas with limited access to water. The degree of sustainable water supply varies across the world, but increasing urbanization and climate change have in later years put pressure on more regions (Campisano, Butler, et al., 2017). Rainwater tanks are now being implemented under integrated urban water management concepts to reduce the use of mains water for typically non-potable water uses. Literature differentiates between two terms for reuse of stormwater. Rainwater harvesting (RWH) commonly describes tanks collecting stormwater from household roofs for domestic water usage. Stormwater harvesting (SWH) consists of the collection of stormwater from drains, creeks, or waterways for reuse at centralised community household or industrial uses (Mcmahon et al., 2008). However, the terms are very close and are often used interchangeably, and RWH is often used for both practices (Akram et al., 2014). Therefore, RWH will be used to describe both practices further in this thesis. A distinction will be made between domestic and non-domestic systems.

Tank-based reuse-systems has a high water-saving potential, as collected volumes can supplement the water supply for outdoor or indoor uses that do not require drinking water quality standard. Possible uses are toilet flushing, laundry, garden irrigation, terrace cleaning, and other sporadic outdoor uses such as car washing (Campisano, Butler, et al., 2017). Examples of implementations also exist for the use of rainwater for thermal energy recovery (Kollo & Laanearu, 2017) and industrial purposes in cooling-towers (Thomé et al., 2019). Despite different uses, all RWH aim to reduce drinking water consumption from centrally supplied sources (Campisano, Butler, et al., 2017; Jones & Hunt, 2010). Differences in uses will likely occur between water-scarce regions and humid regions. While water-scarce regions may use the water for toilet flushing or laundry, humid regions may solely use the water for irrigation or other outside uses (DeBusk et al., 2013). A separate piping network is usually required to connect the tank to appliances for inside use, and one or more pumps are normally used to achieve the required pressure head (Abbasi & Abbasi, 2011).

Multiple countries have experience with RWH over recent years, such as Australia, USA, Japan, and Brazil, with Australia as the leading country. In Australia, RWH tank systems are encouraged as a supplementary water source through financial incentives and regulations such as requirements in building codes for alternative water sources and/or water conservation measures. Rainwater tanks have played an essential part in long-term strategies to secure water supply in Australian cities. Domestic systems are the most widespread technique (Mcmahon et al., 2008; Sharma et al., 2015). Scandinavia has also applied reuse-systems during the last decade. There are projects for innovative solutions such as the town of NYE in Aarhus (COWI, 2014), reuse in Copenhagen (Godskesen et al., 2013) and reuse practices within Hammarby Sjostad in Stockholm (Iveroth et al., 2013).

Norway has historically had great access to fresh-water of high quality. That could be why reuse-systems have not been implemented to a large degree, and one of the reasons why the leakage on water-supply pipes is about 30%. However, climate change will probably result in higher average water temperature, more intense precipitation, and more frequent flooding in surface water sources. These changes will in turn increase the likelihood of larger numbers of microorganisms and larger amounts of organic material, nutrients, and pollutants in water sources. These, together with possibly longer periods with drought, can influence the access to water also in Norway (Ministry of the Environment, 2013; RIF, 2019). As of now, a few incentives to reuse stormwater in Norway exists. The Norwegian Standard, NS 3845:2020: Blue-green factor calculation method and weighing factors (Standard Norge, 2020), stimulate the implementation of open handling of stormwater and include points about the collection of stormwater for irrigation. In addition, stormwater usage in toilets and urinals give points in the BREEAM-NOR manual 2016 (Norwegian Green Building Counsil, 2016).

2.3.2 Water quality aspect

The water quality of the stormwater for reuse will depend on the quality of the water that enters the tank, the processes within the tank and any contamination that occurs in the transport between the tank and the supply point. The quality of the water that enter the tank will depend on catchment material, site pollution and weather conditions, and seasonal variations have been found in studies (Despins et al., 2009). Since a large proportion of RWH systems are based on roof collection for household usage, this has also been the focus for studies on water quality in RWH systems (Abbasi & Abbasi, 2011; Sharma et al., 2015, p.210). Rooftops are expected to be comparatively cleaner than parking lots, sidewalks, and other impervious surfaces but can still contain substantial amounts of heavy metals and nutrients (Abbasi & Abbasi, 2011; Hamdan, 2009).

High lead concentrations and low pH has been identified as the main chemical issues in RWH literature. Multiple studies report lead concentrations above drinking water standard. If tank water is not used for drinking, there is less concern, as the trigger value for lead in agricultural water supply is much larger than for drinking water. This is categorized as unlikely to be exceeded unless there is a specific contamination issue (Sharma et al., 2015, p.217-224). The microbial quality of rainwater is found to depend on the site. Birds and other animal feces have been identified as a leading source of contamination. Especially the first flush can contain substantial amounts of pathogens. Still, for non-potable reuse purposes, this is not described as an issue (Campisano, Butler, et al., 2017).

The storage tank provides an opportunity for water quality improvement due to sedimentation of particulates and precipitation of heavy metals (Despins et al., 2009). In addition, the tank has the potential for further treatment options. These include both pre-storage (debris screens, filters and first-flush diversion) and post-storage measures (post-storage filtration, flocculation and disinfection). First-flush diversion devices have been identified to significantly improve the water quality (Abbasi & Abbasi, 2011; Campisano, Butler, et al., 2017; Despins et al., 2009). The need for treatment will depend on the initial quality of the stormwater and the reuse purpose. If the stormwater is to be used as a potable water source, treatment will be necessary (Sharma et al., 2015, pp. 278–279).

2.3.3 Multiple-use stormwater tanks

Water scarcity and the need for water supply augmentation are not the only reasons to use stormwater reuse systems, as the possibility exists to use RWH systems for traditional stormwater control objectives. If appropriately designed, tank-based RWH systems be adopted as a complementary measure to reduce the frequency, peaks, and volumes of urban runoff (Campisano, Butler, et al., 2017).

When applying stormwater tanks for the dual purpose of peak flow reduction and stormwater reuse, the two goals are opposing. While a full tank is ideal for water conservation, it cannot provide the wanted detention during an event. For a system to efficiently reduce the runoff peak, there must be sufficient room available in the tank (Gee & Hunt, 2016). RTC provides a potential solution to meet both objectives of reuse and peak flow reduction. RTC by controlling the outlet of a tank, or a system of tanks, based on flow, water level monitoring, and rainfall forecast has been shown to reduce peaks by utilizing the storage room more efficiently. Therefore, the tank can remain sufficiently full for reuse purposes during non-critical periods and still achieve peak flow mitigation during storm events (Liang et al., 2019). Roman et al. (2017) demonstrate how the performance of traditional RWH systems can be improved by a Continuous Monitoring and Adaptive Control (CMAC) approach. Advances in information infrastructure, as well as hardware and software solutions, known as the Internet of Things (IoT), can provide new opportunities for cost-effective stormwater handling. IoT can be described as a network that connects all network elements with wireless technology that enables the objects to collect and exchange data (Atzori et al., 2010). The CMAC approach gathers information from on-site sensors and weather forecasts, then uses this data to make automated decisions on how to store and when to release from stormwater collected. Findings from this study indicate that recent advances in technology through CMAC can provide significant performance improvements over conventional RWH systems in both water conservation and runoff control.

Another possibility in order to meet both these objectives is to divide the tank into two segments. In the bottom of the tank, there could be a retention storage where water is extracted to meet user demands. The upper part of the tank could then serve as a temporary holding space for runoff. With a restrictive flow orifice on the outlet, this segment would provide peak flow reduction and be completely emptied prior to the next event. The bottom part would still be preserved for usage (Campisano, Butler, et al., 2017; Gee & Hunt, 2016).

Gee and Hunt (2016) examines to what degree RWH, for both alternate water supply source and to provide detention/retention of runoff, can be enhanced via innovative technologies. The paper look at two-segment tanks with a passive release mechanism versus tanks with an active release control mechanism. The active release mechanism includes a RTC device that automatically releases harvested water based on precipitation forecasts. Water in the active release tank is only released if the forecast predicts an event that will mean insufficient storage capacity in the tank, hence is the water preservation aspect kept. The active control preserves the entire available storage volume for users during dry periods. Two locations in North Carolina, USA, with RWH systems to capture roof runoff and store it for non-potable usage where examined. In this study, both systems provided substantial stormwater mitigation, with the active system performing only slightly better. The addition of either of these mechanisms is said to increase the predictability in which a RWH system is able to provide a certain amount of stormwater mitigation. Without these mechanisms, stormwater mitigation will depend solely on the usage of the stored water. Similarly, Xu et al. (2018) studies how multi-objective RWH systems can be enhanced with RTC by modeling performance. In this study, the active release systems, compared with the passive release systems, showed distinct advantages in reducing overflow frequency and increasing stormwater retention. The passive release systems had a slightly better water supply performance. The active control systems showed an ability to provide centralised control, as well as failure detection which opens up the possibility of delivering a more stable and reliable system. This can then possibly be readily adapted to varying climates over both the short and long term.

2.3.4 Financial viability

Considering the financial viability of RWH is complicated because many factors need to be taken into consideration. Costs include installations, maintenance, operation, and energy use. The primary benefit used in literature is the amount of water and wastewater saved. Predictions about future water prices are often used to calculate the payback periods. Infrastructure savings represent another benefit. Multiple other indirect benefits from RWH systems may not be measured financially due to data limitations and difficulty in quantifying value (Amos et al., 2016).

Campisano, Butler, et al. (2017) evaluates the financial viability of a large number of different RWH systems. The financial evaluation shows widely varying results. The financial viability in many cases is far from being acceptable, with payback periods too long to provide a reasonable return on investment. However, the paper points out that the financial models used only take the advantages purely connected to water conservation into account. Other aspects, as reduction of urban runoff, have often not been considered. Future research should include multiple beneficial aspects under complex engineering, hydrological, economic, and social settings. In this context, it will be a challenging task to quantify and include less tangible factors. Amos et al. (2016) points out that improper considerations of maintenance and operational costs are responsible for many of the conflicting conclusions on the economic viability of a RWH system. Sample and Liu (2014) evaluates the cost/benefit of RWH systems with respect to both water supply and runoff mitigation. The paper concludes that the analysis is very sensitive to changes in water and wastewater prices and that an increase in these rates would make the systems more economically profitable.

DeBusk et al. (2013) points out that, in humid regions where the reuse of the harvested water may be restricted to irrigation or outdoor uses, a second objective may be needed for the system to be worth the effort and to be economically feasible. Because outdoor uses are often seasonal or periodic, secondary objectives, such as stormwater management, should be identified and implemented. However, the paper identifies two problems of RWH systems used mainly for seasonal purposes. They remain full during the non-growing season, and water usage is needed mainly in periods with limited rainfall. The paper also points out that widespread implementation of RWH systems in humid regions in the USA will require regulations or incentives that weigh the cost of implementation. The paper suggests that instituting incentive programs, such as stormwater mitigation credits or tax credits/rebates, will increase implementation.

Gee and Hunt (2016) discusses the cost/benefit of an active release mechanism and a passive release mechanism for two-segment RWH tanks. The active release control is, as predicted, considerably more expensive than the passive release control. The results will depend highly on the site and local conditions. If the active release control could avoid considerably CSO, this would increase the importance and applicability. For small projects, the cost, complexity, and resource requirements of the active release control could hinder implementation. The passive release mechanism is inexpensive and easy to install. The need for human input is limited, thus decreasing the likelihood of user error or neglect. There will most likely be a threshold that dictates which release mechanism that is the most appropriate to use for a given application.

2.4 Stormwater modeling

2.4.1 Stomwater management models

Stormwater models are used to simulate movement across a catchment in response to precipitation with a set of catchment conditions. These models can be classified in many ways. The models can be either deterministic or stochastic, depending on if they include elements of randomness or not. Deterministic models will always produce the same result with the same input. Further, the models can be conceptual or empirical depending on the presence of physical laws in the model. The model can also be classified as continuous or event-based, based on the modeling time period. The models can work as a planning model, operational model, or design model (Akram et al., 2014).

Stormwater computer models can be classified as hydrologic or hydraulic. Hydrologic models simulate the rainfall-runoff process to generate surface and sub-surface runoff, while the hydraulic model route the flow through stormwater infrastructure. To simulate the stormwater runoff most urban catchment models use hydrologic and hydraulic computations for loss modeling, overland flow modeling, pipe or channel flow modeling and modeling of flow through storages. Different models apply different methods to compute these hydrologic and hydraulic responses (Akram et al., 2014).

2.4.2 Stormwater reuse models

Stormwater reuse models will try to predict the performance of the RWH system to e.g. size the tanks, predict demand coverage, or stormwater reduction performance. Several model type exists with varying complexity. Examples include simple tools considering only the variability in rainfall, while other approaches develop analytical formulas (Sharma et al., 2015, p.19-20). A significant proportion of the water recycling models have focused on the RWH system consisting of roof-collection on a household level (Akram et al., 2014). Campisano, Butler, et al. (2017)

give an overview of the modeling tools applied for the analysis and design of RWH systems. The most common approach is to use continuous water balance simulation to make use of historical rainfall observations to generate inflow, with an assumed water demand as outflow. The volume inside the tank is then calculated as a function of time (Basinger et al., 2010).

Campisano, Butler, et al. (2017) defines that a RWH mass/water balance model typically combine interrelated modules which include:

- An inflow model to represent the available water. This is based on synthetic rainfall series or rain gauge data. Temporal datasets range from minutes to months with spatial proximity ranging from on-site rain gauges to regional averages.
- A calculation module which enables tank mass balance simulations to be performed whilst accounting for losses at each time step (such as roof runoff losses, first flush losses, filter losses, tank overflows).
- A behavioral model to represent the water for reuse (rainwater demand). Demand can be taken from literature, historic meter data or real-time metering data.
- An output module which logs, summarises and presents data from each simulation.

Differences in needed complexity will likely occur between typical RWH systems and more complex SWH systems (Mitchell et al., 2008). On a household scale, the module used to turn rainfall to runoff for continuous water balance simulations can be based on the rational formula or variations of this formula. An example is showed in Eq. 1, where Q_t $[m^3]$ is the inflow volume supplied to the tank at time step t, ϕ [-] is the runoff coefficient depending on water losses, A_{TOT} $[m^2]$ is the area and R_t [m] is the rainfall for the timestep (Campisano & Modica, 2015). First flush diversion units and other losses can also be included in the module (Sharma et al., 2015, p.21-22).

$$Q_t = \phi * R_t * A_{TOT} \tag{1}$$

More complex catchment calculations will likely be needed if the system is not based solely on roof collection. These catchments may require a hydrological and/or hydraulic model to generate runoff. The model choice depends on the type of catchment, the availability of catchment data, the level of complexity and the sophistication required in the simulation of catchment runoff response, and the time available for the analysis (Akram et al., 2014; Mitchell et al., 2008). Suitable models for these calculations include SWMM, MUSIC, and WaterCress (Dandy et al., 2019).

The calculation modules have usually been based on one of the two operating algorithms, "yield after spillage" (YAS) and "yield before spillage" (YBS) developed by Jenkins et al. (1978). The YAS and YBS algorithms differ only in if the yield is withdrawn before or after overflow. General conclusions support the use of the YAS operating algorithm for design purposes as it results in a more conservative estimate of water-saving efficiency (Campisano, Butler, et al., 2017). The YAS algorithm can be displayed mathematically as shown in Eq. 2.

$$Y_t = min\begin{cases} D_t \\ V_{t-1} \end{cases}, V_t = min\begin{cases} V_{t-1} + Q_t \text{ - } Y_t \\ \text{S - } Y_t \end{cases} \tag{2}$$

Q_t (m^3) is the volume discharged as overflow from the storage tank, V_t (m^3) is the storage volume, D_t (m^3) is the water demand, Y_t (m^3) is the yield from the storage tank and S (m^3) is the storage.

The results from continuous water balance models may be impacted by the selected time step. Results from Fewkes and Butler (2000) indicate that daily time step resolution may be sufficient if the aim of the analysis is to evaluate the water-saving potential. However, if the model aims at analysing the tank potential to reduce runoff, an accurate analysis may require higher time resolutions. Higher temporal resolution (5 min) is suggested if the purpose is to evaluate the potential of RWH systems in reducing peak flow rates to the drainage system (Campisano & Modica, 2014).

2.5 U.S. EPA SWMM - Storm Water Management Model

The U.S. Environmental Protection Agency (EPA) Storm Water Management Model (SWMM) is a rainfall-runoff simulation model that can be used for both single event and long-term simulations. The model can simulate both runoff quantity and quality and is primarily used for urban areas. SWMM was first developed in 1971 and has been through several upgrades since then. It is widely used throughout the world to plan, analyse, design, and manage urban drainage systems. The current edition is Version 5 (Rossman, 2015). This subsection only includes a short description of the program. For further details, see the SWMM manual (Rossman, 2015).

SWMM accounts for various hydrological processes related to runoff production, for instance including time-varying rainfall, evaporation, snow, infiltration, overland flow, and various types of LID measures. Related to hydraulic modeling, SWMM contains a flexible set of modeling capabilities used to route runoff and external inflows through a drainage system network of pipes, channels, storage/treatment units, and diversion structures (Rossman, 2015).

Every model includes one or more subcatchments. For these, a rain gauge must be assigned to represent the rainfall. The subcatchments are modeled as rectangles, where the user sets the width and area. Further, other properties such as the slope and imperviousness must be selected to best represent the catchment. The flow from the subcatchments can then be led to a junction node and further with links. Other elements that can be included are, for example, pumps, storage units, weirs, and LID controls. Results from a simulation can be presented as tables or graphs, where the user can select the wanted element to analyse (Rossman, 2015).

Snowpacks can be assigned to each subcatchment. The snowpack object contains parameters that characterize the buildup, removal, and melting of snow. A percentage of impervious area can be set as ”plowable”. This can be applied for reads or parking lots where plowing and snow removal occurs (Rossman, 2015).

2.5.1 LID controls

SWMM have LID controls designed to capture surface runoff and provide some combination of detention, infiltration, and evapotranspiration. The LID controls are considered as properties of a given subcatchment. SWMM can model eight different types of LID controls of which bioretention cells, rain gardens, continuous permeable pavement and rain barrels are included (Rossman, 2015).

The LID controls mainly consist of a combination of vertical layers. The different controls vary in what type of layers are included. For each layer, width and other properties can be adjusted. For bioretention cells, infiltration trenches, and permeable pavement systems a drain pipe can be included. SWMM differentiates between bioretention cells and raingardens, where bioretention is a multilayer element with optional underdrain while the raingarden includes fewer layers and does not have an underdrain. During a simulation, SWMM performs a moisture balance to keep of how much that is stored and moves between the different layers. As an example, Figure 2 shows the layers and the pathways between them in a bioretention cell (Rossman, 2015).

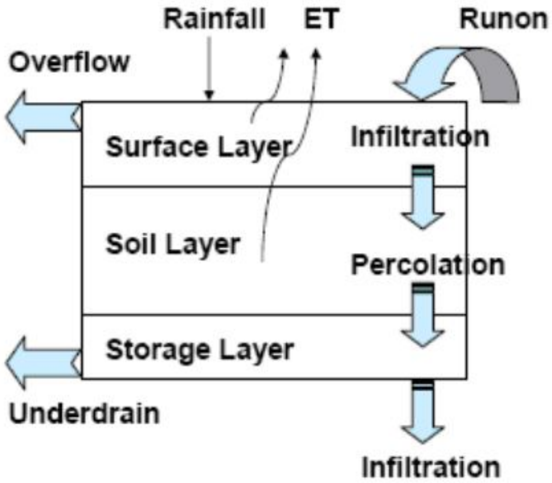


Figure 2: Conceptual buildup of a bioretention cell in SWMM. Source: Rossman (2015)

2.5.2 Modeling reuse in SWMM

SWMM can be used to simulate RWH systems. In general, two options exist, SWMM LID rain-barrel and a storage unit with a control rule (Campisano, Catania, et al., 2017).

The LID rain-barrel option can represent a household stormwater tank with an outlet underdrain flow. Overflow will occur when the tank is full. This option does not allow the user to provide demand-driven patterns of yields from the rainwater tank. However, by managing the underdrain flow, demand can be simulated (Campisano, Catania, et al., 2017). For the rain-barrel, the underdrain flow is driven by Eq. 3:

$$q = C * h^n \tag{3}$$

In Eq. 3 the outflow (per unit barrel area: $q = Q_Y/A_b$) through the barrel underdrain $[m^3/s/m^2]$ is a function of the height h [m] of the stored water in the tank. Coefficients C and n are decided according to the desired outflow (Rossman, 2015). Based on Eq. 3, to achieve a situation where a demand pattern can be withdrawn, n can be assumed to be 0. This removes the dependent of q on the height. Further, appropriate values of C must be chosen to achieve the desired output (Campisano, Catania, et al., 2017).

The storage unit node option can represent reuse systems with different sizes and configurations. Storage units in SWMM are nodes that provide storage volume, and they could physically represent facilities as small as a catch basin or as large as a lake. A volume curve can be added for a storage unit to represent the height/storage relationship (Rossman, 2015). To use the storage unit as a RWH facility, the demand pattern can be represented as a pump with a control rule. The control rule can simulate pump switch on/off. The different outlet types available in SWMM can then also be linked to the storage unit to represent overflow or an outlet discharge (Campisano, Catania, et al., 2017; Gnecco et al., 2017).

3 Description of pilot

The newly constructed ZEB-laboratory will be a living laboratory, an office, and an education building for research on building materials, energy flow, and stormwater management systems. This chapter describes the ZEB-pilot stormwater management system and its connected catchment area.

3.1 Location and site

The ZEB-laboratory has been constructed at a site previously used for parking to NTNU/SINTEF at Gløshaugen (Trondheim, Norway). The site is located 36 m.a.s.l. according to norgeskart.no. Trondheim has an annual average precipitation of 884 mm and an average temperature of 5.2 ^{o}C (Climate-data.org, 2020). The main characteristics of the climate in Trondheim are strong seasonality, short summers, and no predominant dry seasons (Hamouz et al., 2018; Peel et al., 2007).

The surrounding areas of the ZEB-laboratory consist mainly of buildings and impervious areas. The subsoil consists of marine deposits, preferably clay. Infiltration measurements have been made in the area. They conclude that the local masses are mostly dense and that infiltration therefore can not be expected to a significant degree. The ground will only to a small extent be able to accept larger quantities of rainfall (Pedersen, 2020). Figure 3 show the location and site in November 2020 after completion of the construction process.

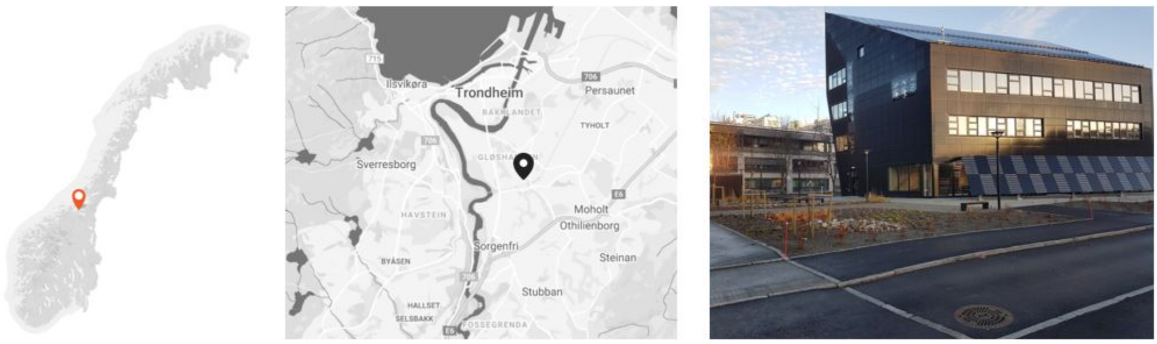


Figure 3: The ZEB-laboratory located at Gløshaugen in Trondheim, Norway. Maps generated with norgeskart.no and Google Maps.

The stormwater management system will manage the stormwater from the site. With the new lab and its stormwater management system, the site is divided into sub-areas for runoff calculations. The areas are shown in Figure 4. The different sub-areas can be described as:

- Area A consists of areas with permeable surfaces with gravel, bushes and permeable cover. Area A also includes bioretention cells.
- Area B is the roof of the ZEB-building. The building has a steep roof.
- Area C is a parking lot and bike/walk areas to the north.
- Area D is mostly existing road areas. For this area the stormwater is already handled and the area will therefore not be included in the following plans.

Figure 4: Overview of areas connected to the stormwater tank at the ZEB-building with piping roughly illustrated. Area A: Permeable surface and bioretention cells; Area B: ZEB-lab roof; Area C: Parking lot; Area D: Existing road. Stormwater tank in blue, located in lower left corner. Adapted from Pedersen (2020).

In the planning of the system has the stormwater runoff from the sub-areas been calculated by Storm Aqua AS. The area drains to a combined sewer pipe. According to Trondheim municipality, the release to the network for a reduced area of 2276 m^2 should be no larger than 6 l/s. Dimensioning precipitation is calculated based on Trondheim municipality guidelines with IDF-curve from Trondheim - Voll, Moholt og Tyholt. The return period is set to 20 years and a climate factor of 1.4 is applied (Pedersen, 2020; Trondheim kommune, 2020). Table 1 show a summary of the runoff calculations for the different sub-areas at the ZEB-lab.

Table 1: Summary of runoff calculations at the ZEB-lab (Pedersen, 2020)

Sub-area	**Area (m^2)**	**Runoff coefficient**	**Reduced area (m^2)**	**Detention need (m^3)**	**Runoff (l/s)**
A	2136	0.54	1163	16.6	3.1
B	505	0.9	454	6.6	1.2
C	732	0.9	659	9.7	1.7
SUM	**3373**		**2276**	**32.9**	**6.0**

3.2 Stormwater management system

The ZEB pilot stormwater management system consists of several bioretention cells and an underground stormwater tank. The different sub-areas, described in the previous section, will all contribute runoff to the tank. In the tank there is an active volume for reuse as well as a detention volume for larger storm events. With these configurations, the ZEB-stormwater management system represents an innovative system for handling stormwater that promotes detention, infiltration, reuse, and water quality improvement.

Area A includes several stormwater control measures. Four bioretention cells are constructed on the left of the building. These are illustrated and numbered in Figure 5. The cell to the north (1) has an underdrain directly to the tank. The two in the middle do not have an underdrain. For these two, overflow from the northernmost cell (2) is lead to the tank, while the overflow from the southernmost (3) is directed to the northernmost cell. For the cell to the south (4), overflow will be lead to a sand-trap south of the tank. A permeable cover of 642.7 m^2 is surrounding the ZEB-lab. The rest of area A consists of gravel-covered walking areas and lawn. An underdrain from the east will transport some stormwater from the areas with permeable cover and lawn. The underdrains are needed based on the limited infiltration capacity of the existing soil (Pedersen, 2021).

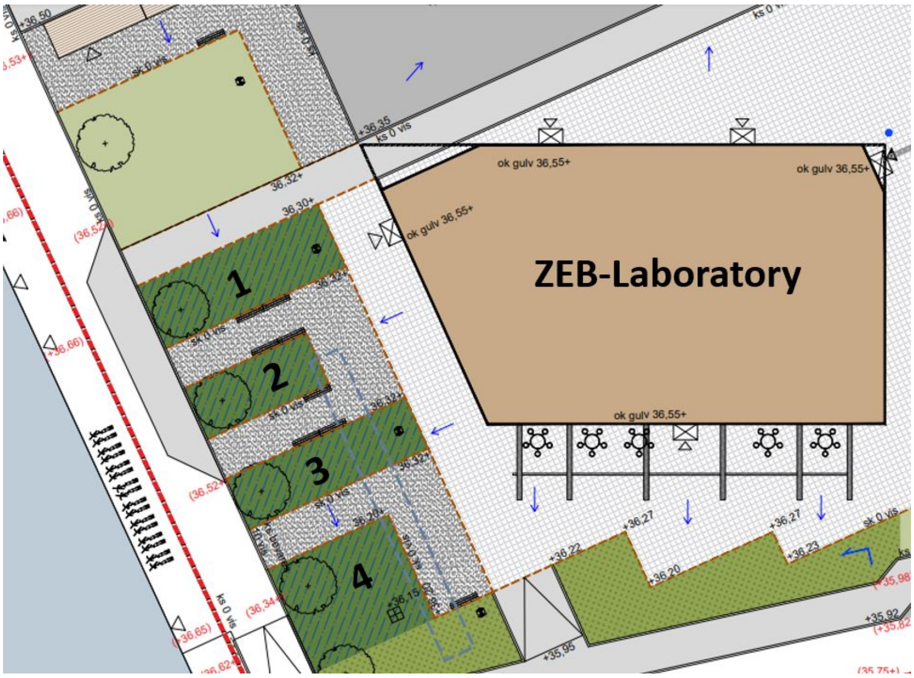


Figure 5: Bioretention at the ZEB-laboratory. Flow path roughly illustrated with blue arrows. Stormwater tank in dashed blue line. Adapted from LINK Landskap (2020).

For the roof (area B), stormwater is led directly to the tank with a pipe. The parking lot (area C) have two drains that go to a pipe leading stormwater to the tank. In total, the tank have six separate inflow pipes (Pedersen, 2021). Figure 6 show a simplified schematic flow chart of the stormwater management system.

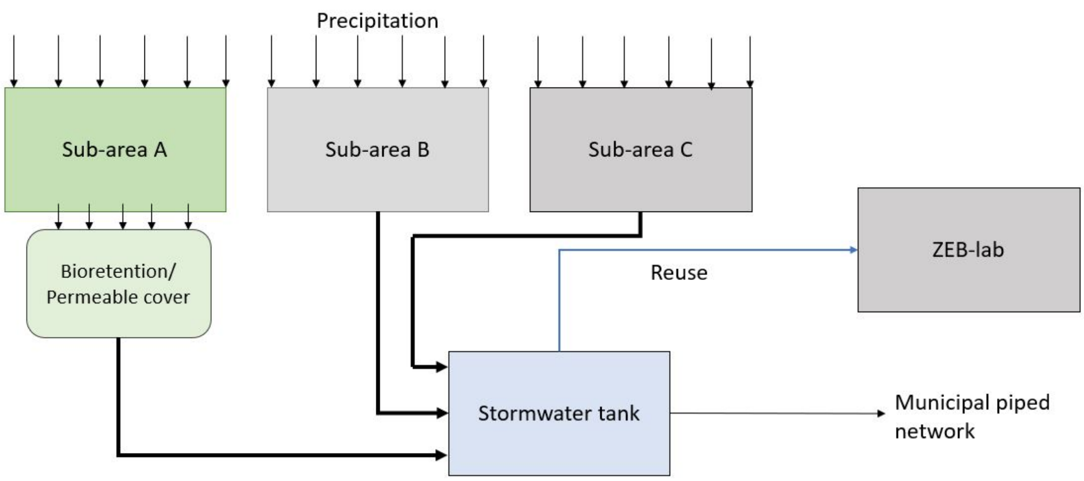


Figure 6: Schematic flow chart of the ZEB stormwater management system. Adapted from Kjellsen (2020).

The stormwater tank is placed in the lower left corner of the site; see Figure 4. The tank is of the type Alma Smart Tank and specifically configured for this site. It is constructed by putting together prefabricated concrete segments. Appendix A show an illustration of the ZEB stormwater tank (Pedersen, 2021). Minor inaccuracies exist in this illustration, and the numbers provided in this section are considered the correct values.

Stormwater enters the tank into a sand trap chamber (4.61 m^3). A concrete wall with a height of 1.2 m separates the sand-trap chamber and the main chamber in the tank. Water above 1.2 m flows over to the main chamber. The main chamber is 17.8 m long, 2.0 m wide, and has a maximum height of 1.5 m. The main chamber has an active volume for reuse (18.76 m^3) as well as a detention volume for larger storm events (32.92 m^3). The active volume will stay in the tank if it is not applied for reuse. At this time, a pumping system and outlet pipe for the reuse water are not installed, and consequently, there is not yet applied any reuse for the active volume (Pedersen, 2021).

The outlet in the ZEB stormwater tank is a passive restrictive orifice outlet of type FluidGate DN100 and manages the outflow from the detention volume. Outflow from orifice outlets are given by Eq. 4, where A is the orifice area, H is the water level above the opening, C is the outlet coefficient and Q is the discharge. The outlet in the ZEB stormwater tank is designed to let out 6 l/s at the maximum water level (Pedersen, 2021).

$$Q = C \cdot A \cdot \sqrt{(2 \cdot g \cdot H)} \tag{4}$$

Figure 7 shows the outlet configuration in the stormwater tank. The bottom of the outlet is 0.558 m above the bottom of the tank. This height can be altered to adjust the relationship between the active volume and detention volume. There are possibilities to install RTC-devices on the outlet for active control at a later point. More details about the outlet as well as the inlet is provided in Appendix B (Pedersen, 2021).

Figure 7: Outlet configuration in the ZEB-pilot stormwater tank. Source: Pedersen (2021)

4 Methodology

4.1 Literature review

The literature review presented in this master's thesis has been conducted in two stages. The first part of the review was developed in "TVM4510 - Water and wastewater engineering, specialization project" in the autumn of 2020 (Kjellsen, 2020). The specialization project acted as a pre-study and established the theoretical background on bioretention, stormwater tanks, and stormwater reuse systems. In addition, the introduction in this master's thesis is based on the introduction from the pre-study. The second part of the literature review were performed in this master's thesis. Here, the result from the review in the pre-study has been adapted and shortened. Further, reuse modeling approaches in literature have been investigated and a theoretical description of SWMM has been added. The literature review was conducted using academic search engines, such as Google Scholar, Oria, and Web of Science (WoS).

A large number of articles have been found in the literature review. The articles used in this thesis have in general been chosen based on several criteria, such as:

- Content: The articles must provide useful information related to the topic.
- Relevance: The articles should be relevant to the context of urban stormwater management. Articles from regions that have comparable conditions will normally be more relevant than articles from areas with less comparable conditions. This could be e.g. climatic, social, economic conditions.
- Number of citations: Highly cited research articles indicate that the source is trusted by many. When considering new articles, this have less importance as they often have not been able to build up the number of citations yet.
- Place published: Articles published in recognized journals are expected to have a high academic standard.

4.2 Instrumentation, monitoring and data collection

The ZEB lab and its stormwater management system are newly constructed, and consequently, no previous monitoring had been performed, and no instruments were installed in the system. The pre-study (Kjellsen, 2020) planned the instrumentation and started the continuous monitoring of the tank water level. This master's thesis continued instrumentation, with the installation of a weather station and the establishment of an outflow curve. Performance data for the system has been collected throughout the monitoring period.

A tipping bucket rain gauge for monitoring rainfall is installed on site, as well as instruments for measuring wind speed and temperature. Monitoring of precipitation, temperature, and wind speed provides important data for analyzing the performance of the stormwater management system. Data is collected from these three devices with a data-logger and transmitted with the 2G cellular network once a day. These devices run on battery. Data is available in both hourly time-steps and minute time-steps. Several issues occurred with this station, which limited the working period. The first precipitation gauge installed did not register any precipitation, and troubleshooting together with IT-service showed that the bucket was defective. A new gauge then had to be installed and configured to the correct setup. Both gauges could not handle precipitation at minus degrees, which also made the originally planned working time-period shorter. Figure 8 show the station installed on the site.

Figure 8: Weather station installed at the ZEB-laboratory site

The water level in the stormwater tank is continuously monitored using TD-Diver data-logger pressure sensors from Van Essen Instruments. The TD-Diver is a submersible data logger for long-term water level monitoring using a pressure sensor. The pressure sensor measures the equivalent hydrostatic pressure of the water above the sensor diaphragm to calculate the total water depth (Van Essen Instruments, 2016). When the TD-Diver is submerged, it measures absolute pressure, which is the atmospheric pressure and water pressure added together. To find the water level, a Baro-Diver which is not submerged, measure atmospheric pressure. The atmospheric pressure can then be used to convert the data from the TD-Diver into water level in a process called barometric compensation. The barometric compensation can be performed in the program associated with the divers, Diver-Office (Van Essen Instruments, 2018). From monitoring, the divers were shown to have a fixed measurement bias. Calibration of the TD-divers can only be performed by the manufacturer. Therefore, this bias was found by manually measuring the water level in the tank on several occasions and comparing this to the diver readings. The diver readings could then be corrected to match the actual water level.

In addition to the use of TD-Divers for measuring water level, one CTD-Diver is used to monitor conductivity in the tank as an indication of the water quality. The CTD-Diver measures water level similarly as the TD-Diver, but is in addition equipped with a 4-electrode conductivity sensor for measuring the true or specific electrical conductivity of the water. A change in conductivity may be caused by factors such as changes in water flow or increasing/decreasing pollution or salinization (Van Essen Instruments, 2016).

The data from data-loggers have to be collected manually within a time period decided by the recording time-step for the loggers. Determining the best time-step relates to the objectives of the monitoring and to what degree it would be possible to collect data often. As the ZEB-pilot is located at NTNU, the tank is easily accessible. Small time-steps would provide the most detailed outcome and improve analysis for high flow events. However, the data would have to be collected more often and be harder to analyse. Larger time-steps would make the data more manageable and reduce the number of manual data collections. Even so, details in high-flow events could be lost. Based on these assessments, for monitoring the water level, a time-step of one minute is chosen.

Table 2 summarise the instrumentation and shows the monitoring time period.

Table 2: Summary of instrumentation to monitor the ZEB-tank performance

Description	**Instrumentation**	**Time period**
Rainfall, wind, temp	Wind: Gill WindSonic M Temp: Campbell Scientific CS215 Rain: Casella tipping bucket rain gauge	06.05.21 - 20.05.21
Water level in tank (sand-trap)	TD-Diver AZ102	15.11.20 - 20.05.21
Water level in tank (main chamber)	TD-Diver AZ200	15.11.20 - 20.05.21
Conductivity in tank	CTD-Diver K6849	15.11.20 - 20.05.21
Atmospheric pressure	Baro-Diver S2994	15.11.20 - 20.05.21

The outflow from the ZEB-stormwater tank is not monitored. The outlet opening was designed based on the theoretical relationship between the outlet opening and the height above the outlet to make the outlet release 6 l/s at the maximum water level (see section 3.2 and Appendix B). In order to verify the actual outflow and by that increase the accuracy in modeling, an outflow test was performed. The test was performed with the assistance of personnel from Trondheim Bydrift.

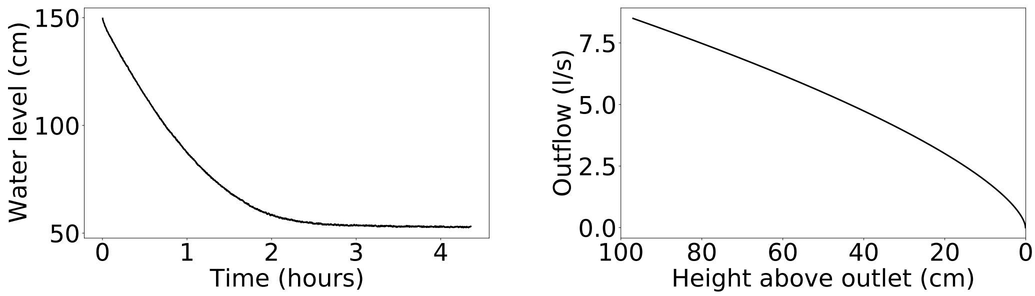
In the test, two divers were submerged in the main chamber of the tank, recording at timesteps of 10 seconds. The tank was then filled with water from the municipal drinking water network. From a nearby manhole, a fire-hose was connected and lead to the inflow side of the tank. When the tank reached the maximum water level, the water was shut off. The divers were then left in the tank to monitor the change in water level until the detention section of the main chamber was fully drained. Figure 9a shows the hose connection in the nearby manhole, and Figure 9b shows the main chamber in the tank at a maximum water level after filling.

(a) Hose connection to the water distribution network

(b) Main chamber at a maximum water level

Figure 9: Test to establish an outflow curve for the ZEB stormwater tank

After the test, data from the test period was collected from the divers to be further analysed to establish the outflow curve. The water level data measured by the divers are shown in Figure 10a. To produce the outflow curve, the water level data first had to be smoothed. Then, the outflow in l/s could be found using the change in water level for a timestep and the known volume of the tank. The outflow curve is shown in Figure 10b where the outflow is given as a function of the water level. It must be noted that this outflow curve only will be valid for the current outlet opening.



(a) Diver-data

(b) Outflow curve

Figure 10: Water level data and outflow curve from outflow test

In order to use the outflow curve in model simulations, an outflow curve equation can be made from the curve in Figure 10b. This was performed using the trendline option in Excel. Eq. 5 show the outflow function where Q is the outflow in l/s, and H is the height above the outlet in meters.

$$Q = 13.251 \cdot H^3 - 23.564 \cdot H^2 + 19.542 \cdot H \quad (5)$$

4.3 Model setup

To model the ZEB stormwater management system for analysis, a two-step model has been created. In the first step, SWMM is applied in order to turn precipitation into tank inflow data. Further, a behaviour storage module Python-script based on the level-pool routing method simulates the water balance in the tank. The model enables possibilities to investigate both stormwater detention performance and demand coverage. Simulations can be based on actual rainfall data or design rain data to analyse long-term performance or investigate short-term events.

4.3.1 Model selection

The ZEB-stormwater management system represents a non-domestic RWH facility where stormwater retention is the main focus. For the rainfall-runoff process, the system includes more elements than the traditional RWH system that must be considered. Stormwater will be generated from the three sub-areas, and these areas will have different properties. The bioretention cells and drain pipes in sub-area A make a more complex runoff situation. Further, a rainfall-runoff model of the ZEB-pilot must also take snow accumulation and storage into account for long-term simulations as precipitation during winter often will be snow. In SWMM, these processes and considerations can be handled.

Related to the behavior storage module, as the tank also has controlled discharge based on water height, the outflow needs to be based on both demand and the discharge curve for the outlet. Traditional tank water balance calculation modules such as the YAS algorithm (Eq. 2) have therefore been considered not applicable for this model. The ZEB-tank water balance simulation could have been implemented in SWMM. The LID rain-barrel option is not usable for tanks with multiple outflows, but with the use of the storage unit node, this could most likely be handled (see section 2.5.2). Even though, this option is not pursued further in this thesis.

By creating a separate script for the behaviour storage module, the specific properties of the ZEB-tank could be included. The developed script based on the level-pool routing method handles both demand and orifice outflow and accepts time-series with demand. This enables a simple way to test different scenarios. For each simulation, the model saves lists, max/min values, and other information. The script is transparent for the user, and the code can easily be modified and applied for similar tanks and systems later.

SWMM is a common tool to model stormwater collection and transport through catchments. Furthermore, the script developed to simulate tank behaviour has, as a continuous water balance simulation, many similarities with the frequently applied YAS/YBS algorithms. Even so, the model created in this thesis represent an innovative way to simulate the performance of multi-objective reuse systems that have complex catchments.

4.3.2 Rainfall-runoff module

The catchment and inflow pipes to the tank have been developed in SWMM 5.1 to simulate the process from precipitation to tank inflow. The ZEB-stormwater management system and its connected catchment areas are described in Chapter 3. In general, the different sub-catchments are created and provide runoff to junctions and further with conduits to an outfall node. The inflow series to the outfall node is then used further as input to the behaviour storage module that simulates the tank water balance.

Figure 11 show an illustration of the model setup in SWMM. Catchment sizes and conduit lengths are purely illustrative. To handle the runoff situation from sub-area A, several sub-catchments have been created which generates inflow to multiple LID controls. Table 3 show an extract of the parameters selected for each catchment. In Figure 11 and Table 3, SB is the ZEB-roof (sub-area B), SC1-2 is the parking lot (sub-area C) and SA1-4 is sub-area A. In Table 3, width, slope, Imperv and Zero-Imperv are estimated based on the properties of the areas. Overland flow parameters (N-Imperv and N-Perv) and depression storage parameters (Dstore-Imperv and Dstore-Perv) are chosen based on values provided in the SWMM manual (Rossman, 2015).

Table 3: Extract of SWMM subcatchment parameters

Parameter	**Subcatchment**									
	SB	SC1	SC2	SA1	SA2	SA3	SA4	Bio1	Bio 2	Bio 3
Area (ha)	0.0505	0.0432	0.03	0.1	0.03	0.01	0.01	0.005	0.003	0.004
Width (m)	15	10	8	7	6	4	4	3	3	3
% Slope	45	0.1	0.1	0.5	0.1	0.1	0.1	-	-	-
% Imperv	95	85	85	5	15	15	15	-	-	-
% Zero-Imperv	95	5	5	5	5	5	5	-	-	-
N-Imperv	0.015	0.015	0.015	0.015	0.015	0.015	0.015	-	-	-
N-Perv	0.15	0.15	0.15	0.15	0.15	0.15	0.15	-	-	-
Dstore-Imperv	1.8	1.8	1.8	1.8	1.8	1.8	1.8	-	-	-
Dstore-Perv	3.81	3.81	3.81	3.81	3.81	3.81	3.81	-	-	-
Lid-Control	-	-	-	1	-	-	-	1	1	1

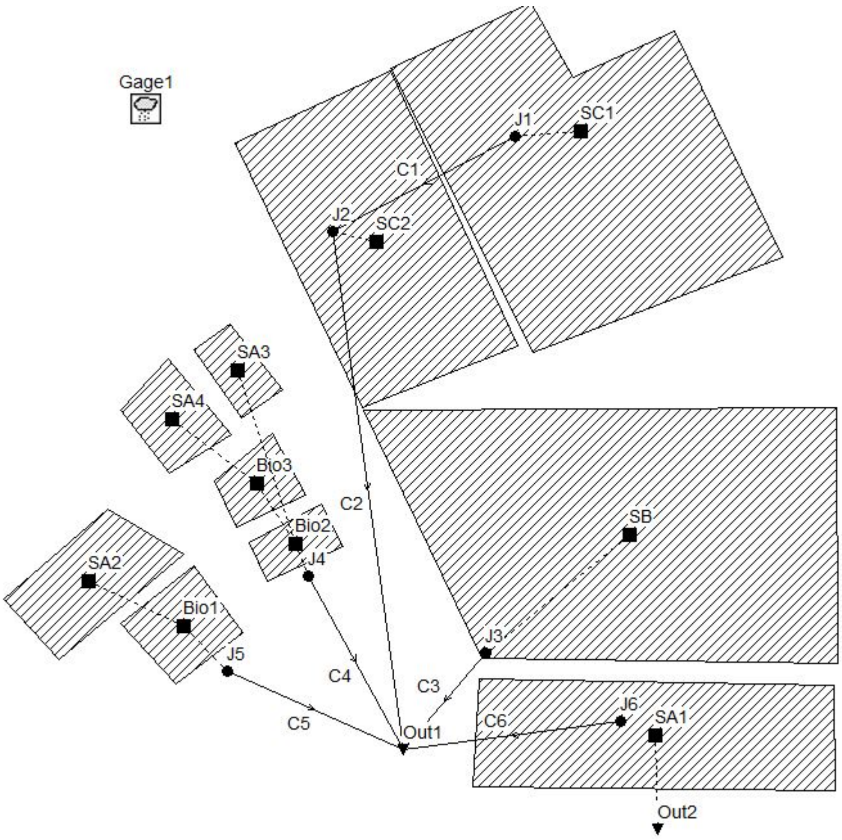


Figure 11: Illustration of the model setup in SWMM

The conduit properties are shown in Table 4. The max. depth (pipe diameter) is given in design documents (Pedersen, 2020). Manning's n is chosen based on the SWMM manual (Rossman, 2015) recommendation for closed plastic pipes. The lengths and slopes are based on estimations from maps.

Table 4: Extract of SWMM conduit parameters

Parameter	**Conduit**					
	C1	C2	C3	C4	C5	C6
Max. depth (m)	0.16	0.16	0.16	0.16	0.16	0.16
Length (m)	15	30	15	5	10	20
Manning's n (-)	0.013	0.013	0.013	0.013	0.013	0.013
Slope (%)	0.7	0.7	20	4	2	1

For the ZEB-laboratory roof and the parking lot, conduits are connected from the catchments directly to the outfall (Out1). These catchments are modeled as mostly impervious. The roof is modeled as 95% impervious with limited depression storage and with a slope of 45 degrees. The parking lot is divided into two subcatchments in SWMM (SC1 and SC2), where they generate runoff to two nodes. These two nodes represent the two drains at the parking lot. For these two nodes, ponding is allowed in the model. This represents the possibility that water will pond on the surface of the parking lot and contribute to inflow later.

For the permeable pavement surrounding the ZEB-laboratory, the permeable pavement LID control has been applied as a part of subcatcment SA1. Of the total area of SA1, the permeable pavement occupy 64.4%. The underdrain is connected to a junction (J6), and further to the outfall (Out1) by a conduit. Information about the permeable pavement is obtained for layer thickness and void ratio. The other parameters for the LID control is defined from literature or based on assumptions. An overview of the permeable pavement LID control parameters applied in SWMM is shown in Appendix C. Overflow from SA1 is lead to a separate outfall (Out2). This configuration is based on that only the drain flow from the catchment will reach the tank and is therefore necessary to ensure more realistic tank-inflow values from the pavement. However, it must be noted as a simplification, as some surface outflow from the permeable pavement likely will infiltrate in the vegetation located around and contribute to underdrain outflow later.

The bioretention cells have been handled separately. These cells are illustrated and numbered in Figure 5, with the same numbering in Figure 11. For the cell to the north (1) with an underdrain to the tank, this is created as a bioretention cell LID control with an underdrain. The drain flow goes to a connected junction and further to the outfall by a conduit. A separate catchment (SA2) provides the inflow. Cell 2 and 3, where only the overflow will reach the tank, are configured as similar bioretention cell LID control, but with elevated drain pipes to represent overflow pipes. Two small catchments (SA3 and SA4) provide inflow to these. The overflow from cell 3 is routed to cell 2, and the overflow from cell 2 is routed to the tank by a conduit. The cell to the south (4), where the overflow is directed to a sand-trap located below the tank, is not included in the model. Limited information about the layer buildup of the bioretention cells has been obtained. Bioretention parameters have therefore mostly been selected based on literature or assumptions. An overview of the bioretention LID control parameters applied in SWMM is shown in Appendix C.

Three separate snowpacks is created to model the snow storage behaviour of the different sub-catchments for long-term simulations. The parking lot is subject to plowing during the winter. The ZEB-laboratory roof have snow losses and a faster melting process. This is taken into account in the snowpacks.

4.3.3 Behaviour storage module

A deterministic, numerical routing model has been developed to model the water balance in the ZEB stormwater tank. The model can be applied both for continuous long-term simulations and for event-based simulations. This module is written in Python, and the script is shown in Appendix D. For programming language, Python is chosen solely based on previous experience. Any other programming language could most likely also have been selected for this model.

This script is developed based on the principles of the level-pool routing method. The level-pool routing procedure is typically used to investigate the effects of a detention pond/basin/tank on a runoff hydrograph and can be applied in the design process (Park et al., 2012). The basis of level-pool routing is the mass balance equation. The change of the storage in a basin can be described as a mass balance equation over time as shown in Eq. 6, where I is the inflow rate, O is the outflow rate, S is the storage, and t is the time (Park et al., 2012).

$$\frac{dS}{dt} = I - O \tag{6}$$

The mass balance equation for a defined time step can be written in finite difference form and rearranged as shown in Eq. 7, where Q is the outflow (Park et al., 2012).

$$\frac{S_2 - S_1}{dt} = \frac{I_1 + I_2}{2} - \frac{Q_1 + Q_2}{2} \tag{7}$$

In Eq. 7, S_2 and Q_2 are both unknown as they depend on each other (outflow based on water height). One possibility to solve Eq. 7 for each time-step is then to use iterations. The iteration process can be described as follows, where Q_2* is a guess for the next outflow:

1. Set $Q_2* = Q_1$
2. Compute S_2 using the water balance eq. for Q_2*
3. Find a new Q_2 for S_2
4. Compere with initial guess. Repeat until $|Q_2*$ - $Q_2| \approx 0$.

To do the iteration process automatically for each time-step, an optimization function can be applied. Multiple optimization modules are available in Python. For the script developed, the "scipy.optimization" package is used with the Nelder-Mead method to minimize the absolute value of the guess Q (Q_2*) and the actual Q (Q_2).

When starting a new simulation with the behaviour storage script, initial values can be changed in the "initial values"- section. The desired time-step (dt) can then be changed. The name of the SWMM input file need to be set. Also, if demand is to be included in the model, type 'YES' under DEMAND. If demand is included, then the name of the demand time-series will also need to be added. This file need to have the same length and same time-step as the SWMM input file. A leakage factor in l/s can also be added under initial values.

PySWMM is applied to get the data from the SWMM file to the Python-script. PySWMM is an interface to SWMM that allows modelers to interact with the SWMM model for optimization, controls, and post-processing results (McDonnell et al., 2020). With pySWMM, the script accesses the SWMM file and runs the model. Date/time, inflow data (l/s) and precipitation data (mm/hr) are then saved from the simulation. These data can then seamlessly be used further in the model. The precipitation data is not used in water balance calculation but is imported for plotting.

Separate functions are created for the different calculations in the model. These functions can be described as:

- IM: Average inflow for the time-step: $IM = \frac{I_1+I_2}{2}$
- Storage: Calculation of tank storage (based on Eq. 7): $S_2 = S_1 + (IM * dt) - (\frac{Q_1+Q_2}{2} * dt)$
- Water level: Calculation of water level based on storage. For a rectangular tank: WL = S/A_{tank}, where S is the storage volume and A_{tank} is the area of the tank.
- Release: Calculate the outflow based on water level and demand. Above the outlet threshold, outflow from the detention storage is given by the outflow curve combined with demand. The outflow curve can be either the theoretical outflow curve based on Eq. 4 or the actual outflow curve showed in Eq. 5. If the water level is below the height of the orifice, the outflow is given only by demand. The demand is added in the model as a time-series. Demand is only withdrawn if the tank volume is above 1 m^3. Leakage is also included based on the leakage factor set under initial values.
- Diff: The function to be minimized in the iteration process. Returns the absolute value of the difference between the guessed outflow and the actual outflow.
- Optimizer: Performs the iteration process. Uses "scipy.optimizer" to minimize the diff-function. Returns updated outflow when difference is below an acquired tolerance.

The "main-function" in the model then performs the calculation with the functions listed above for each time-step. First, IM is calculated and "guess_Q" is set equal to the previous discharge (Q_out). Then, the actual discharge is found by the optimizer-function. If tank storage is below demand (demand can not be met in full), no water is extracted. If demand is not met for a time-step, this is registered. The model registers if demand is not met by checking if the discharge Q is lower than the demand for the time-step. Further, the storage and water level for the time-step is calculated by utilizing the storage and water level functions. If water level exceeds the maximum level, the date and time of overflow are registered. The "main-function" then returns lists of water level data (m), storage volume data (l) and outflow data (l/s). These lists can then be saved or used to plot results.

Finally, the model prints the results from the simulation. Maximum water level, minimum water level and maximum discharge are printed for each simulation. If demand is included, the model print date and time when demand was not met and print the total demand coverage (%) for the time period. For analysis of events, the model prints the time of peak inflow and the time of peak outflow/water level.

4.3.4 Model calibration, validation and limitations

Calibration

The rainfall-runoff SWMM module is based on many parameters, some of which are known based on the physical system and others which are based solely on literature or assumptions. In general, model calibration involves setting a parameter range for some of the uncertain parameters and optimizing these to make the model perform as close as possible to desired values (Hernes et al., 2020). Calibration of a SWMM model can, for instance, be performed with the use of interfaces such as pySWMM (McDonnell et al., 2020) and SWMMr (Leutnant et al., 2020). The calibration parameters must be chosen and assigned a reasonable parameter range. These parameters are then adjusted within their range to make the model perform close to an assigned dataseries which contains measured values or the desired output. The calibration can be performed automatically or manually. Automatic calibration can be performed with the use of an optimization algorithm to automatically find the best parameter dataset. Manual calibration is performed by adjusting the parameters manually. With many parameters involved, manual calibration can become very time-consuming (Ndiritu, 2009). An objective function such as the NSE (Nash–Sutcliffe model efficiency coefficient) (Eq. 8) can be applied to evaluate the goodness of fit (Hernes et al., 2020). What NSE that can be judged as acceptable will depend on the model type and intention. However, in general, NSE above 0.5 can be regarded as satisfactory (Moriasi et al., 1983).

$$NSE = 1 - \frac{\sum_{n=1}^{N} \left(Q_t - \hat{Q}_t\right)^2}{\sum_{n=1}^{N} \left(Q_t - \bar{Q}_t\right)^2} \tag{8}$$

where t is the time interval, Q is the observed runoff, $\hat{Q}$ is the simulated runoff, and $\bar{Q}$ is the mean observed runoff.

Restricting factors

Model calibration requires data of a certain quality to compare against. For the ZEB-stormwater system, at this point, the only measured values are for tank water level. As the different inflow pipes are not monitored, there is no control of the contribution from the different sub-areas. The connected sub-areas to each inflow pipe have multiple parameters in SWMM. The danger in calibrating a model based on many parameters on limited data, is that some parameters will compensate for others and by that creating a model that performs well on a single event, but in fact do not represent the physical system. Furthermore, for two of the bioretention cells only the overflow will go to the tank. Without specific monitoring of the inflow pipe from these, it will be impossible to estimate if or when this has occurred during the monitoring period.

Model calibration of the ZEB-pilot is further complicated by leakage from the tank (see section 5.1.1). The leakage is hard to quantify accurately, and the sand-trap chamber would need to be full before water enters the main chamber. The sand-trap chamber is not included in the model on the basis that without leakage, the water level would stay at the threshold of overflow to the main chamber. With a leakage, depending on the dry period in advance of an event, the sand-trap would first need to be filled to the threshold and therefore cause a delay and reduction in main chamber peak water level.

The outlet in the tank was initially not configured according to the design of the tank (see section 5.1.1). The period of monitoring with the correct outlet configuration was limited to only a short period, limiting the possibility of performing a calibration of the module.

Performance evaluation

The model performance have been evaluated on the period with both correct outlet configuration and local precipitation data. The monitoring period with the correct outlet was from 12.04.21 to 20.05.21, while the weather station only was operative from 06.05.21 to 20.05.21. No large events were recorded during this time-period, but some minor events occurred. To perform a model evaluation test, the precipitation data collected from the local weather station is used as input to the model. The simulated water level is then compared with the water level readings recorded by the divers.

In the model simulation, the initial water level is set equal to the monitored initial water level, and the leakage factor applied is 0.0025 l/s. Initial saturation levels for the LID-controls in the rainfall-runoff module are set to 0% based on limited precipitation in the days before simulation start. Initial model evaluation produces a NSE (Eq. 8) value of 0.61. This result already indicates that the model predicts system performance well. Based on the little time-period, and the lack of possibility to validate on an other time-period, a calibration was performed manually, adjusting only three parameters: The slope and imperviousness of the parking lot and pipe length to the parking lot. These are all uncertain parameters, and are only adjusted slightly within their probable range. No more adjustments are performed due to the restricting factors previously discussed in this section. After the manual calibration, the evaluation of the goodness of fit with NSE produces a value of 0.83. Figure 12 shows the actual water level from monitoring together with the simulated water level for the time-period the weather station was operative.

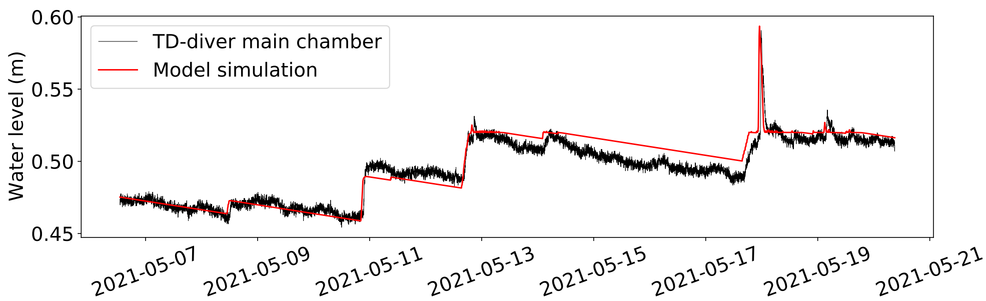


Figure 12: Performance evaluation of the model on monitored water level data from 06.05.2021 to 20.05.2021. ZEB weather station data used as input to the model. NSE value obtained: 0.83.

Based on the NSE obtained and the visible similarity between observed data and the simulated water level (Figure. 12), the model represents the system satisfactorily for this time-period. Even so, for events, the model inflow-time seems to be slightly early. This is especially visible when looking closer into the event occurring on the 17. of May. During dry periods, the model only needs to estimate the leakage to predict the actual performance. Therefore, the NSE value is exaggerated by the dry periods and would likely be lower for periods with frequent events. The LID-controls were likely not providing much inflow to the tank during the time-period evaluated based on the limited amounts of rainfall experienced. LID-control contribution will probably create a more complex tank-inflow situation for more significant events or more extended periods with precipitation. Since no validation could be performed, the similarity obtained in this simulation must still be regarded as well within the expectations.

When running the model on precipitation data from a nearby weather station in Trondheim (Risvollan) for the same time-period, a negative NSE value is obtained. This is due to differences in amounts and timing of the precipitation. When the stormwater system experienced an event on May 17, the Risvollan station registered almost no rain. This highlights the importance of local precipitation data for the evaluation of model performance.

Limitations

The developed SWMM model is based on several assumptions. Many details about the stormwater system before the tank is unknown, such as the buildup and layout of the bioretention cells, and the flow capabilities of the underdrains. As a result, most LID parameters are based only on literature. In addition, the length of pipes and depth of the manholes are chosen based only on estimates from maps. This lack of information limits the possibility of the rainfall-runoff module to represent the physical system accurately. More details about the system, an extended monitoring period, and further calibration of the rainfall-runoff would provide more certain simulation results. However, the module does take the important processes into account, such as peak flow reduction capabilities of the LID controls in sub-area A and snow storage.

Since the calibration and validation performed are limited, the model results should be assessed with uncertainty. The time-period evaluated must be considered as too short for certain conclusions. This period may not be representative for normal performance. With no more observed data to compare results to, the model intention is mainly to estimate the stormwater control potential and reuse capacity of the system, not to recreate or predict the exact performance. The model performance evaluation indicates that the model is capable of estimating system stormwater control potential and reuse capacity.

4.4 Data preparation

4.4.1 Precipitation data

The weather monitoring station installed at the ZEB-laboratory site have only measured a short time-period (from 06.05.21 to 20.05.21). To analyse longer time-periods nearby precipitation stations must then be employed. Risvollan precipitation station is located in the Trondheim region, close to the ZEB-laboratory site. Therefore, data from Risvollan is applied for long-term analysis on stormwater detention and for reuse scenarios. These long-term data is made available by supervisor Knut Alfredsen. Precipitation and temperature data for the period of 01.01.2016 - 31.12.2020 is retrieved for the long-term analysis.

4.4.2 Design rain

To analyse the system on high intensity precipitation events, design rainfall events has been created. The IDF (Intensity-Duration-Frequency) - curve from Risvollan precipitation station is applied to create the design events. IDF-curves for Norway are available through the Norwegian Centre for Climate Services (NCCS). Data in the IDF-curves is available with return periods of 2-200 years (NCCS, 2021). The return period is the average time interval in years between the occurrence of a rainfall of a given intensity or higher (Ødegaard, 2014). A return-period of 20 years is selected for analysis of design as recommended by Trondheim kommune (2020). The ZEB-stormwater management system was also initially designed based on a 20-year return period (Pedersen, 2020). In addition, a climate change factor must be added to account for an expected increase in rainfall intensity. Based on Trondheim kommune (2020) the climate factor should be 1.4 for return periods lower than 50 years. For analysis of more extreme precipitation events, return periods of 50 and 200 years are selected. For the return period of 200 years, the climate factor used is 1.5.

Based on the IDF-curve with a return period and the climate factor, symmetrical hyetograms can be created. Symmetrical hyetograms are applied as high-intensity rainfalls rarely will have a constant intensity, and because the maximum intensity often occurs some time after the start of the event (Ødegaard, 2014). The symmetrical hyetogram, shown in Figure 13, uses timesteps of 5 minutes and has a duration of 60 minutes. The return period is set to 20 years, and the climate factor applied is 1.4. Similarly, symmetrical hyetograms are developed for design rainfalls with return periods of 50 and 200 years.

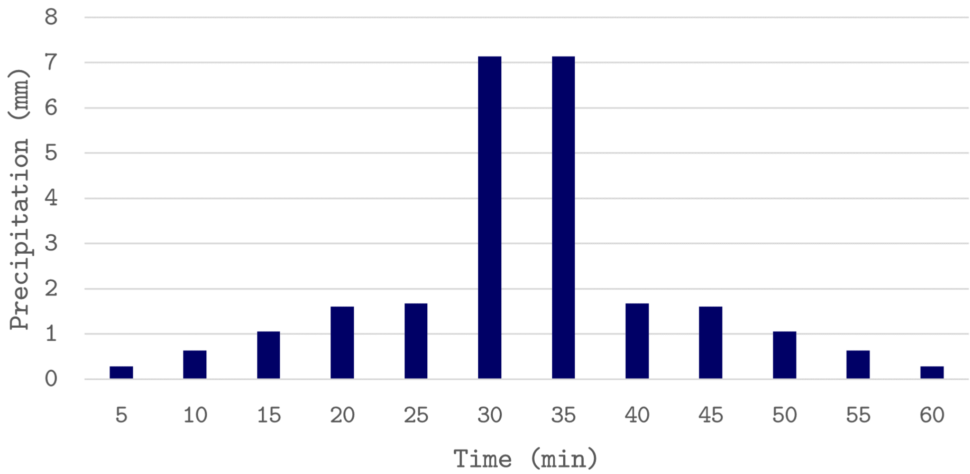


Figure 13: Symmetrical hyetogram based on the IDF-curve from Risvollan precipitation station in Trondheim. Data with a 20 year return period and a climate factor of 1.4.

4.4.3 Demand data

Demand data represents user behaviour. Demand data can typically be taken from literature, historical meter data or real-time metering data (Campisano, Butler, et al., 2017). For the ZEB-laboratory, no real water demand data-series is available. In addition, demand data-series for comparable buildings have not been found in literature.

Estimates of roughly how much water is typically used for, for example, toilet flushing in office buildings exist from various non-academic sources (e.g. EPA (2012)) . This can be used to make very rough estimates of this consumption. The ZEB-lab is estimated to have roughly 70 people present during working hours (Tore Kvande, personal communication 12.03.21). By estimating a total daily water usage for each person of 50 liters and that toilet flushing stands for 40% of this consumption, the daily toilet water usage of the ZEB-lab is 1400 l. A time-series is created for toilet-flushing where this usage is spread over the working hours five days a week. However, this time-series only give an indication of the actual toilet water usage in the ZEB-lab. Information about specific water usage or more data on building usage must be obtained to perform a more certain analysis on the demand coverage the tank can provide for this end-use.

Estimates on other usages, such as irrigation and bike washing, will likely be even more uncertain. These uses will be sporadic and highly variable. Even so, irrigation scenarios are investigated with the model. This is implemented by modifying the ”release”-function in the behaviour storage model especially for this analysis. This modification is shown in Appendix E. Precipitation data is imported to the script from the rainfall-runoff module. During the months of June, July, and August, irrigation is implemented if three days pass without precipitation. Estimates on how much water is needed for irrigation can not be accurately made, so several irrigation intensities are tested to see the coverage provided and the irrigation volume that can be supplied.

As the demand data is limited and uncertain, the maximum water consumption capacity of the system is analysed. In this analyses, different fixed consumptions are tested to see how much water the system can deliver with varying degrees of coverage.

4.4.4 Input data SWMM

SWMM requires a specific data format for the precipitation time series. The series must be date/time/value where the date is entered as month/day/year (Rossman, 2015). Data obtained from the local weather station and the data from Risvollan therefore needed to be transformed to this format before entering the SWMM model. SWMM also requires specific formats for the input climatology. A user-prepared climate file contains station name, year, month, day, maximum temperature, minimum temperature, and optionally, evaporation rate, and wind speed. These are given as daily values. If evaporation rate and wind speed is not available, an asterisk should be entered instead (Rossman, 2015).

For longer time-series, manual conversion is impossible or excessively time-consuming. Therefore, to perform these conversions quickly, short Python-scripts were created. Scripts to convert obtained data from Risvollan to SWMM precipitation input-file and SWMM climatology input-file are shown in Appendix F. The general concept of these scripts is to iterate line by line in the given data and rearrange each line to the correct format. Missing values are handled automatically. These scripts are adjusted to fit the obtained data from the Risvollan climate station and will therefore need minor adjustments if implemented for other stations.

5 Results and discussions

The following chapter presents and discusses the results related to the research questions. First, the performance of the ZEB stormwater management system during the monitoring period is analysed. Then, the systems ability to perform on design events and historical precipitation data are discussed by running scenarios through the model. Finally, the reuse possibilities for the system are discussed based on capacity considerations from system modeling and local conditions.

5.1 ZEB-pilot performance

The ZEB-pilot stormwater management system performance has been monitored from December 2020 to May 2021. In this period, the water level in the tank sand-trap chamber and main chamber, and conductivity in the main chamber have been observed. Climatic conditions on the site have also been monitored for a part of this period.

5.1.1 Findings

Leakage

From the first data collection, it was clear that water disappeared from the tank without the water level reaching the outlet threshold. During dry periods, the water level in both chambers had a steady decrease. This trend was especially visible in the sand-trap chamber, which should have a stable water level at 120 cm. Figures 14 and 15 illustrate this for a part of the monitoring period for the main chamber and sand-trap chamber.

Figure 14: Main chamber tank leakage. Example from monitoring, 15.01.2021 to 01.03.2021.

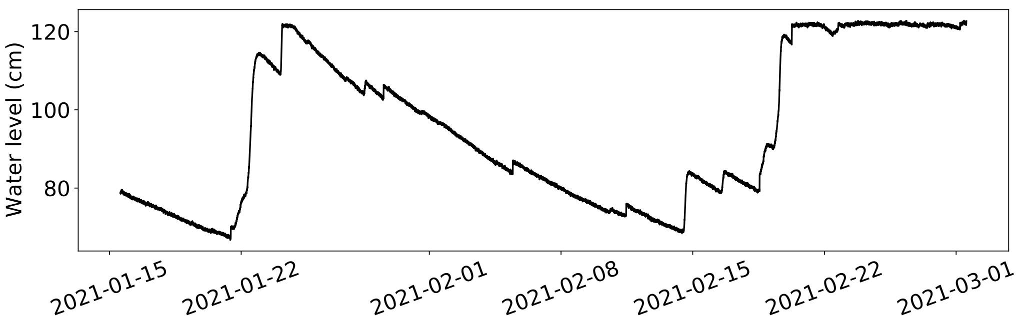
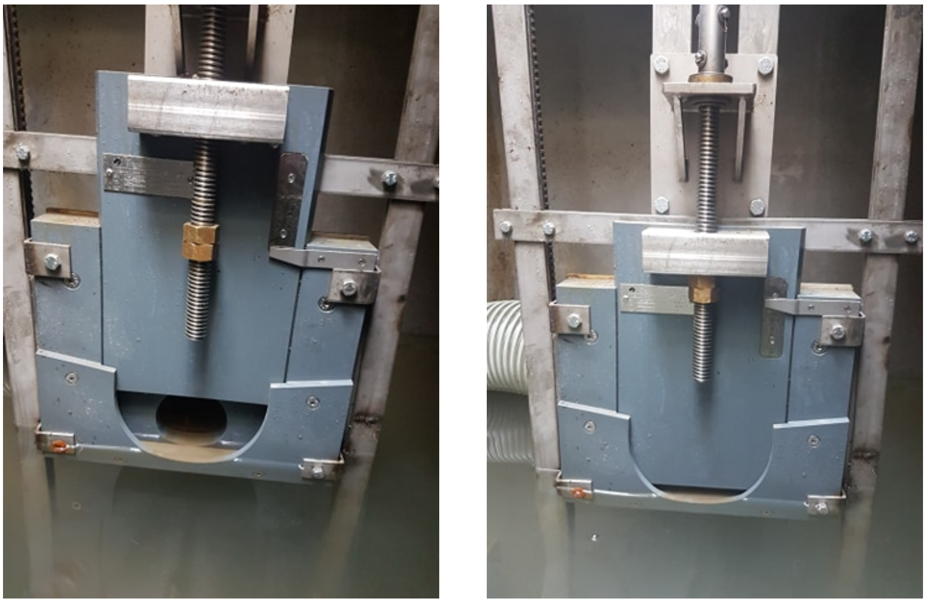


Figure 15: Sand-trap tank leakage. Example from monitoring, 15.01.2021 to 01.03.2021.

Evaporation from the tank is deemed negligible during winter, and it is unlikely that the cause of this decreasing trend is instrumentation error as all instruments showed similar trends. By consulting the producers of the tank, the likely explanation is leakage between the sand-trap chamber and the main chamber and leakage out of the tank from the bottom drain valve in the main chamber. Another possible explanation could be leakage through the concrete segments to the native soil. However, this is deemed unlikely by the manufactures because of previous experience and tests. Leakage from the tank does not have any severe effects on tank detention performance but will lower the tank reuse capacity (see section 5.4.1). In addition, the leakage complicates accurate modeling of the tank as the sand-trap chamber does not have a fixed water level and because the leakage is difficult to quantify accurately. Based on the observations, a leakage factor of 0.0025 l/s from the main chamber is estimated. This factor can only be regarded as a rough estimate as the leakage also likely varies with the water level.

Initial wrongful outlet configuration

The monitoring and observations revealed that the outlet was not configured according to the design of the tank. Appendix B show the intended and designed outlet opening to manage the release according to guidelines. In the construction process, the outlet lid was left open, making the outlet release water much faster. Figure 16a shows the outlet as installed with the lid open. When discovered, the outlet opening was adjusted by the author to 28 mm as intended in the design of the system. This is shown in Figure 16b. If not adjusted, this configuration would make the tank detention potential limited. All data gathered before this discovery was therefore not representative of what should be the tank performance.



(a) Outlet with lid open (b) Outlet with lid at 28 mm opening

Figure 16: Before and after correction of outlet opening

Outflow test

The outflow test, described in section 4.2, was performed after adjustment of the outlet lid. This test revealed that even with the outlet opening adjusted to an opening of 28 mm the tank has the potential to release more water than intended in design. The test revealed that at a maximum water level, the tank could release about 8.5 l/s instead of the intended 6 l/s. Figure 17 shows the outflow curve created based on the outflow test compared to the theoretical outflow curve used in tank-design. The difference can not be described as substantial. Under normal conditions with the current opening, the outflow will be well within the intended maximum outflow. Even so, the opening could be considered reduced to lower the maximum potential outflow to design levels. How much reduction that will be enough to reduce the maximum outflow to maximum design outflow is difficult to assess, but a few millimeters could be enough. In the simulations, the theoretical design outlet curve is applied. This is decided to make simulation results usable also if the outlet is adjusted later.

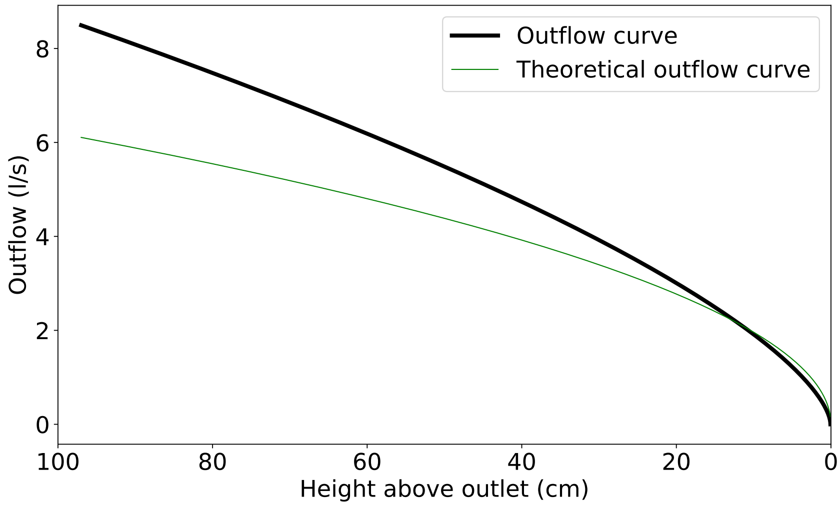


Figure 17: Outflow curve from outflow test compared to theoretical curve used in tank-design

Outlet height

Early water level measurements provided lower values than expected with the designed outlet height above the tank floor. The height was therefore measured manually. These measurements of the outlet height showed that the outlet is placed 0.52 m above the bottom of the tank instead of the designed height of 0.558 m. To this date, this has not been adjusted, but for normal operation the difference is negligible. The height measured by the divers was still lower than the actual water level, which indicated that the divers have a fixed bias. This bias could be adjusted by using the manually measured water levels. The designed outlet height of 0.558 m is still applied in the modeling of scenarios.

5.1.2 Stormwater control

Figure 18 show the performance of the stormwater system for the period of monitoring after the outlet was reduced to an opening of 28 mm. No high intensity events occurred during this period. The maximum water level for the period was 0.59 m, 7 cm above the outlet threshold. This was recorded on an event with 4.6 mm precipitation within 20 minutes on 17.05.21. The leakage is visible for this time-period as well with a minimum water level of 0.45 m recorded (7 cm below the outlet). The sand-trap water level was more or less stable at the threshold for the time-period, indicating frequent inflow to the tank. This is also visible in Figure 18 for the main chamber, where small frequent oscillations in water level can be observed. During the periods with no precipitation, this can be expected to be the contribution from the drain pipes in the area.

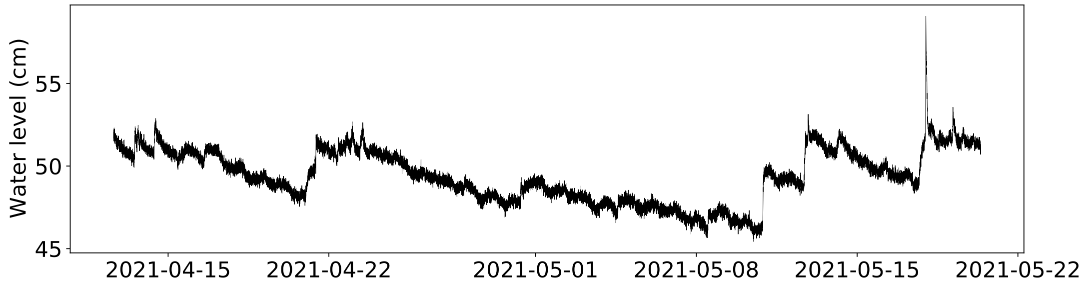


Figure 18: Water level recorded from monitoring in the ZEB-tank main-chamber

5.1.3 Water quality

The conductivity in the main chamber of the ZEB stormwater tank has been monitored for about six months. The conductivity measured ranges between 0.08 - 0.7 mS/cm with about 0.15 mS/cm as a typical value for the time-period. A change in water level can explain the larger conductivity values of up to 0.7 mS/cm as they were recorded during events. The measured values from the tank are above typical conductivity levels of 0.001 mS/cm for natural freshwater (Ødegaard, 2014). Even so, for non-potable purposes, it is difficult to assess if this will cause any problems. The results from conductivity measurements only indicate the ionic content of the water. To further assess the water quality, other analyses should be made, for instance on the content of heavy metals.

5.2 Stormwater control potential

The following section shows the system detention potential on short-term events and long-term data investigated with the model.

5.2.1 High precipitation design events

The performance of the system on design rain events with return periods of 20, 50 and, 200 years has been investigated by applying symmetrical hyetograms as input to the model. In the following events, the initial water level in the tank is set to the outlet threshold of 0.558m above the tank bottom, and the initial saturation level of LID-Controls is set to 30%. The model time-step applied is 1 minute to capture the event peaks.

Figure 19 shows the performance of the ZEB stormwater management system for a 20-year design rain. The maximum water level in the tank for the event is 1.13 m. Peak inflow to the tank is estimated to occur 40 minutes after the event starts, while the peak outflow is estimated to occur one hour and two minutes after the event begins. The maximum discharge for this event will be 4.67 l/s. This simulation indicates that the system can handle events of this magnitude.

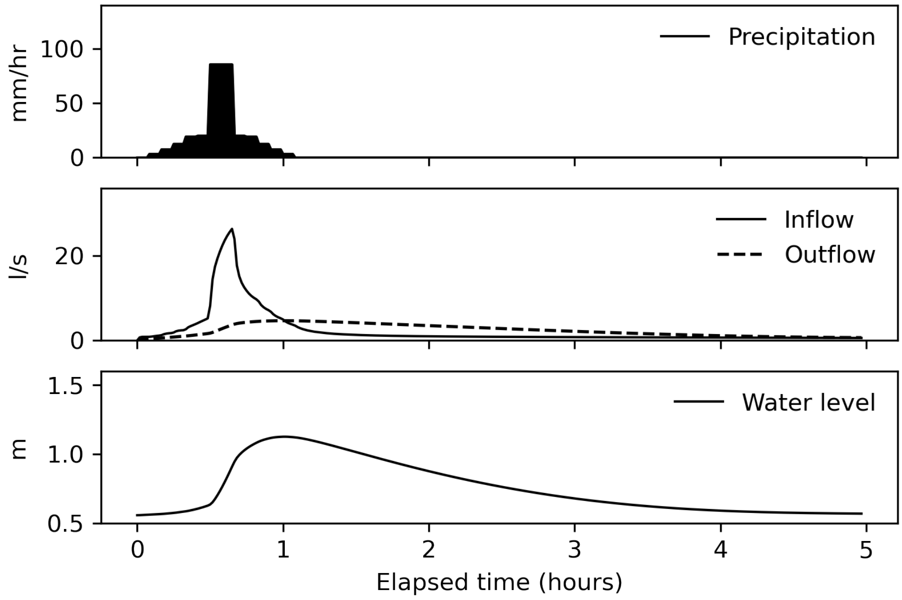


Figure 19: Design rain event performance, 20-year return period.

Figure 20 shows the performance on an event with a return period of 50 years. This event gave a maximum water level of 1.23 m, which occurred after one hour and two minutes and provided a peak outflow of 5.07 l/s. This simulation result indicates that the system can handle events with a 50-year return period.

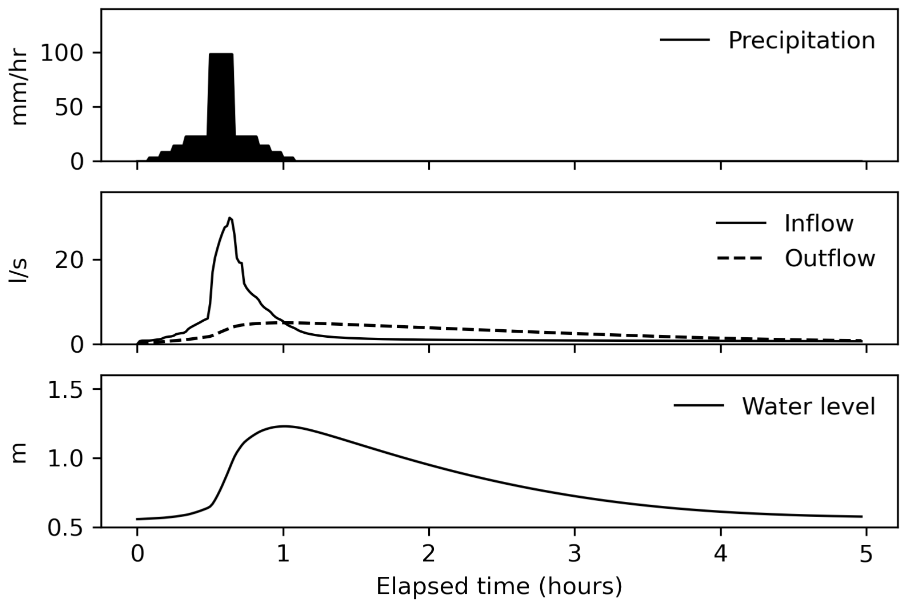


Figure 20: Design rain event performance, 50-year return period.

For the extreme event with a return period of 200 years, the tank will almost reach the maximum water level of 1.5 m. Figure 21 shows the result of the simulation. The model does not handle overflow specifically, except reporting when the maximum level is reached. The ZEB-tank has no overflow pipe or other overflow system. In a situation with a higher return period than the event simulated, the inflow pipes will likely fill up and stay with water. If extreme enough, surcharge of manholes might occur. Even so, based on the simulations in this section, the maximum level in the tank will rarely be reached.

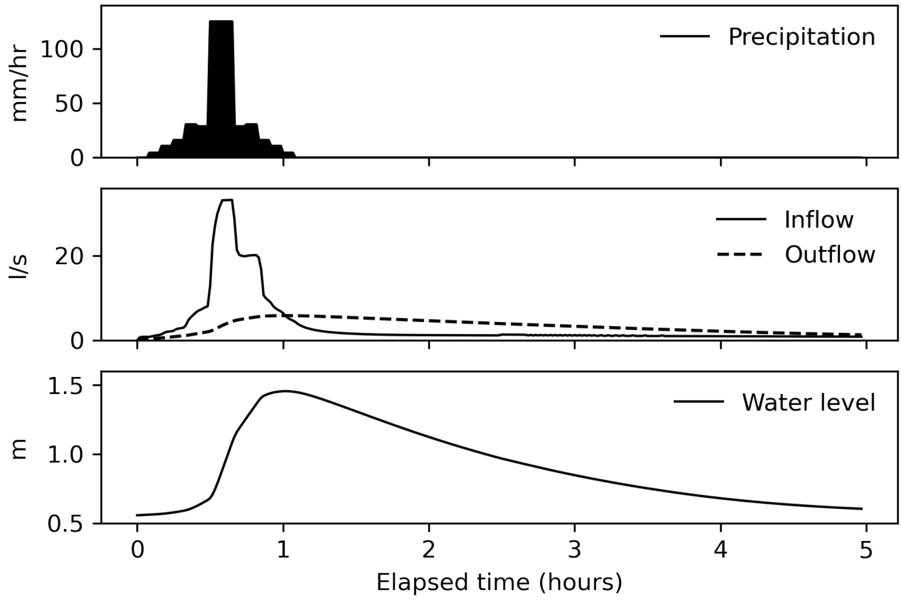


Figure 21: Design rain event performance, 200-year return period.

Initial saturation levels of the permeable pavement and bioretention cells have an impact on the simulation result. The initial saturation levels of the LID-controls have been varied between 10%, 30%, and 70% to see the impact this makes on design event performance. Table 5 shows the tank's maximum water level for the three design events investigated with varying initial saturation. These results indicate that the initial saturation of the LID-controls is not critical for the ZEB stormwater management system's performance on design events. This is likely because a considerable amount of the total catchment area is not connected to a LID-control. The inflow from the parking-lot and the ZEB-roof, which is also the main contributors to peak inflow, as shown in subsection 5.2.2, is not affected by the initial saturation. In addition, the LID-controls slow the peak inflow so that it does not occur simultaneously as the peak from the impervious areas.

Table 5: Maximum water level in stormwater tank for design events with varying initial saturation levels

Initial saturation LID-Controls	**Maximum water level (m)**		
	20-year	50-year	200-year
10%	1.09	1.19	1.42
30%	1.13	1.23	1.45
70%	1.17	1.27	Full

5.2.2 Subcatchment contribution

As of this moment, the contribution from the different subcatchments is unknown as a consequence of no inflow pipe monitoring. The flow in the inflow pipes are therefore analysed with the model to give an indication of the subcatchment contribution. Pipe flow analysis of the rainfall-runoff module indicates that, as expected, the roof and parking lot are the main contributors to fast runoff and stand for a considerable amount of the peak inflow.

Figure 22 shows an example of subcatchment contribution based on a 20-year design rain with initial saturation levels of 30%. Here, the flow in the pipes in l/s from the different subcatchments developed in the rainfall-runoff module in SWMM is shown (see Figure 11 for illustration of the SWMM setup with names on the pipes). The parking lot (C2) gives the largest contribution to the peak inflow, while the impervious roof with a steep slope also quickly provides inflow to the tank (C3). The permeable pavement underdrain (C6) gives a lower, more spread-out inflow to the tank. The underdrain from bioretention 1 (C5) provides only a small contribution in this scenario.

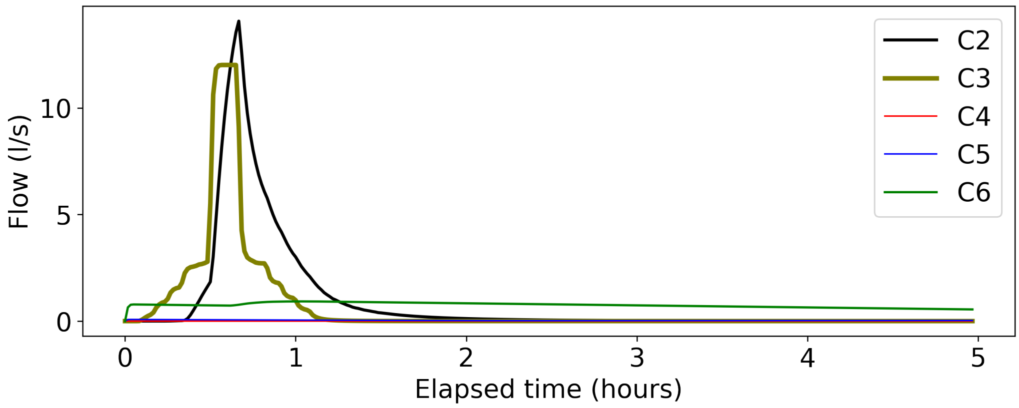


Figure 22: Subcatchment flow contribution on design rain event with 20-year return period. Initial saturation of LID controls set to 30%.

Figure 23 shows the sub-catchment contribution based on a 200-year design rain with initial saturation levels of 30%. Similarly as for the 20-year design rain, the parking lot (C2) and the roof (C3) provides fast inflow to the tank. However, in this simulation, ponding occurred on the parking lot, which causes the roof to provide the largest peak. In this high precipitation intensity scenario, much of the water reaching the permeable pavement is expected to end up as surface overflow. The permeable pavement underdrain (C6) therefore only experience a slight increase compared to the 20-year scenario. The underdrain from bioretention 1 (C5) provides a larger contribution in this scenario, but the peak is delayed and low compared to the parking lot and the roof. Bioretention 2 and 3 (C4) provide inflow only when they overflow. The time that the overflow will occur is uncertain and depend highly on initial saturation. In these examples, with 30% initial saturation, overflow did not occur, and they did not contribute to tank inflow.

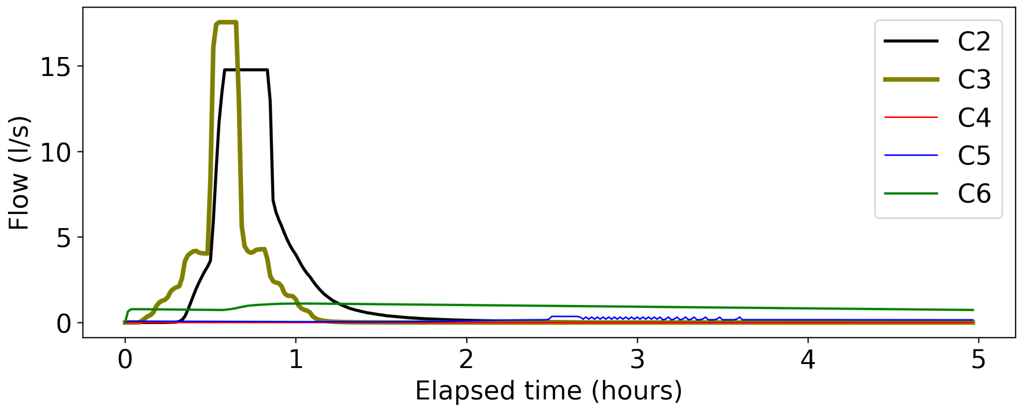


Figure 23: Subcatchment flow contribution on design rain event with 200-year return period. Initial saturation of LID controls set to 30%.

5.2.3 Long-term analysis

The model has been run on precipitation and climate data from the Risvollan weather station for the last 5-years (01.01.2016 - 31.12.2020). This simulation is carried out with time-steps of 5 minutes to reduce the computational power required. It is recognized that this time-step to some degree can round off the peaks, but time-step testing reveal that the impact is small. The initial water level is set to the threshold level of 0.558 m. No leakage is included in the simulation. Figure 24 show the performance. In this simulation, the highest water level recorded was 1.06 m resulting in a maximum discharge of 4.39 l/s. This was recorded on a large event with an intensity of about 70 mm/hr in June 2020. For the rest of the period, the simulation gives water levels mostly below 0.8 m. These results are in compliance with the results from modeling high precipitation events. During the majority of precipitation events, most of the detention section in the tank will stay unused.

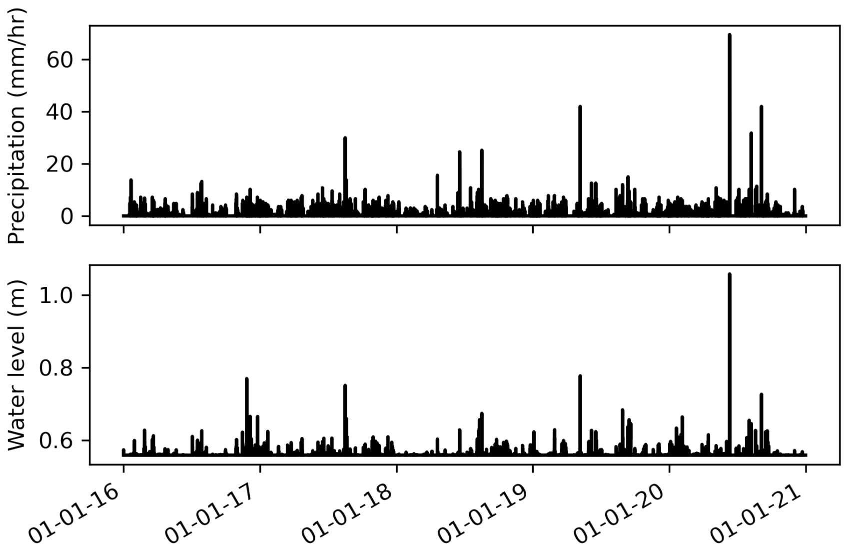


Figure 24: Tank performance on 5-year historic precipitation from Risvollan weather station.

5.3 Tank design evaluation

The tank was initially designed based on a 20-year design rain and a climate factor of 1.4. The rational formula (Eq. 1) was applied to calculate runoff from the sub-areas with an assumed time of concentration. The runoff was then routed through a reservoir model to find the detention need in the tank. In the tank design, the LID controls in sub-area A were only taken into account with the use of a reduced runoff coefficient in the rational formula and a longer time of concentration (Pedersen, 2020).

The results from modeling high precipitation events indicate that the tank is slightly oversized. The results demonstrate that the tank can handle 20-year and 50-year events and only just reach maximum water level for 200-year events with high initial saturation levels. As shown in sub-section 5.2.2, for high precipitation events, the main contributors to tank-inflow will be the ZEB-roof and the parking lot. The LID controls provide a significant peak reduction, which is not accounted for when applying the rational formula. In addition, a part of sub-area A does not contribute inflow to the tank since the bioretention overflow pipe from the south bioretention cell leads to the manhole after the tank. Therefore, the catchment area used in the design is larger than the actual contributing area to tank inflow. However, even with simplifications in design, the initial tank design based on simpler formulas is relatively close to model results.

5.4 Potential stormwater reuse

The relevance of stormwater reuse in urban areas has increased in later years based on urbanization and climate change (Campisano, Butler, et al., 2017). Predictions indicate that these causes can influence the future access to fresh water also in Norway (Ministry of the Environment, 2013; RIF, 2019). For the time being, in humid regions like Norway, seeing stormwater reuse together with stormwater management can increase the feasibility of reuse systems (DeBusk et al., 2013). Stormwater reuse in Norway will be as a secondary water source, similarly as in other developed countries. The aim is then to reduce drinking water consumption from centrally supplied sources for non-potable purposes.

The ZEB stormwater tank has a volume preserved for reuse, as described in subsection 3.2. Uses for this volume are not yet determined, and equipment needed for reuse, such as pumps and pipes, is not currently installed. The ZEB-tank was constructed based on rules on maximum stormwater discharge set by Trondheim municipality (Trondheim kommune, 2020). The reuse of stormwater can therefore be considered as a secondary objective for the system.

5.4.1 Capacity of water available for reuse

Capacity for outlet heights

The ZEB-stormwater tank's capacity has been analysed based on precipitation data from the last 5-years from Risvollan. In this analysis, fixed consumptions are simulated with the model to find the demand coverage the tank can provide for each scenario. No leakage is included in the simulations. Time-steps of 10 minutes is applied. Table 6 show the demand coverage obtained for three different outlet heights; the designed outlet height of 0.558 m and two test heights of 0.3 and 0.8 m. The outlet height of 0.8 m is tested because the results from simulation of high precipitation events indicate that the tank can handle 20-year events even with an outlet height of 0.8 m. The design objectives for stormwater control can then still be met with an increase in outlet height. The outlet height of 0.3 m is tested to further evaluate the impact of outlet height on reuse capacity.

Table 6: Tank reuse capacity. Based on 5-years of precipitation data from Risvollan.

Demand (l/day)		**Coverage (%)**	
	Outlet: 0.3 m	Outlet: 0.558 m	Outlet: 0.8 m
400	97.3	100	100
1000	82.0	91.3	95.0
1500	70.5	81.2	86.6
2000	62.6	72.3	78.5
3000	51.5	59.6	64.5
5000	38.5	44.4	47.9

Based on the model simulations, as shown in Table 6, the maximum daily demand that can be covered at all times with the design outlet configuration is 400 l. However, this can be more than doubled and still be covered 91.3%. If accepted that water will not be available at all times, demands up to 2000 l/day can still be covered 72.3% with the design outlet configuration.

The decrease in outlet height to 0.3 m will lower the coverage the tank can provide. The simulations shows coverages of about 10% lower than for the design outlet height. Simulations with the outlet height of 0.8 m shows an increase in demand that can be covered. Nevertheless, the tank will still not be able to provide coverage at all time for the capacities tested above 400 l/day. This indicates that the variability in rainfall is an important factor when it comes to reuse capacity. Larger reuse volumes such as this can only partly compensate in periods with low precipitation or in longer cold periods during winter.

Impact of leakage on reuse capacity

To evaluate the impact the leakage has on reuse capacity, demand scenarios are tested with the estimated leakage from the ZEB-tank of 0.0025 l/s. Table 7 shows the coverage for two demands previously tested without leakage (see Table 6). These results indicate that the leakage will have a significant impact on reuse capacity. For instance, with an outlet height of 0.558 m and a demand of 1000 l/day the coverage is reduced from 91.3% to 86.2%. These results highlight the importance of stopping the leakage if reuse is to be implemented.

Table 7: Tank reuse capacity with a tank leakage of 0.0025 l/s. Based on 5-years of precipitation data from Risvollan.

Demand (l/day)		**Coverage (%)**	
	Outlet: 0.3 m	Outlet: 0.558 m	Outlet: 0.8 m
1000	75.1	86.2	90.6
2000	58.6	67.9	74.1

RTC

RTC of stormwater tanks and stormwater reuse systems have been shown to increase performance in multiple cases (Liang et al., 2019; Roman et al., 2017; Xu et al., 2018). RTC, by controlling the outlet based on water level and forecasts, can improve peak reduction performance and make more water available for reuse (Liang et al., 2019). This requires the implementation of various hardware elements in the tank, which will increase the cost (Gee & Hunt, 2016; Schütze et al., 2003). An implementation of RTC would also increase the complexity of the system, which increases the possibility of errors in the system. As shown in section 5.2, the tank can effectively reduce peaks, even for high flow events with the current two-segment configuration. An implementation of RTC would therefore depend on how large demand the tank should cover. However, regardless of demand, as a research facility, implementation of RTC would provide the opportunity to assess the possible benefits of RTC, which could benefit design processes for similar systems later.

5.4.2 Reuse possibilities

The literature on stormwater reuse focuses mainly on RWH on a household level with a cistern collecting water from the household roof (Campisano, Butler, et al., 2017). As a larger research building, the ZEB laboratory can provide some different opportunities and possibilities even though probable implementations may be similar to those for a household.

Irrigation and washing are suggested in the literature as objectives for reuse on the household level in humid regions (DeBusk et al., 2013). Irrigation and bike washing can be the most likely implementations for the reuse-water on the ZEB-site. The site has plant and grass growth that may require irrigation during dry periods. Bicycle racks are also located on the site, which could make the site a natural place for a bike washing station. However, these purposes are seasonal, and irrigation will be mostly relevant during dry periods. Even though, irrigation and bike washing may be easier to implement than other usages as they do not require any configurations inside the ZEB laboratory.

Irrigation is investigated with the model as a continuous demand if the number of dry days during summer exceeds three days. Table 8 shows the coverage provided and irrigation volume supplied with three different irrigation intensities. These results indicate that the tank can provide much water for irrigation during summer. However, with the dry periods experienced in the 5-year simulation scenario, the tank will occasionally be empty, highlighting the limitation of seasonal reuse purposes.

Table 8: Irrigation demand coverage. Based on 5-years of precipitation data from Risvollan. Irrigation implemented for summer as a continuous withdrawn during dry periods.

Irrigation during dry periods (l/s)	**Volume supplied ($m^3/year$)**	**Coverage (%)**
0.005	7.2	89.4
0.01	14.2	88.0
0.03	28.7	59.3

For inside use, toilet flushing represents a large non-potable consumption. Model simulations on a probable daily toilet demand of 1400 l (implemented for workdays all year) show that the tank can provide a coverage of 90.6%. This daily toilet demand is based mostly on assumptions and only gives an indication of this usage. Based on this uncertainty, other probable toilet flushing demands are also tested with results shown in Table 9. These results indicate that the tank could cover a large proportion of the toilet flushing water in the ZEB-laboratory if implemented. In addition, the activity at the laboratory is probably lower during the summer, where typically, the longer dry periods will occur. However, as the laboratory was not configured for inside use of tank water during construction, inside use will now likely require the implementation of a separate piping system. Nevertheless, for other similar systems later, toilet use may be the most relevant implementation.

Table 9: Toilet demand coverage. Based on 5-years of precipitation data from Risvollan. Daily demand implemented as a continuous withdrawn on weekdays.

Toilet flushing demand (l/workday)	Coverage (%)
1200	93.7
1400	90.6
1600	87.5

The coverage the tank can provide for inside or outside uses depend on the length of the dry periods and the intensity of the rainfalls. Long periods without inflow will cause the tank to reach empty, while during intense precipitation events, water will be lost through the orifice outlet. Therefore, if climate change provides more intense precipitation and more extended dry periods, this will lower the tank reuse potential. As the simulations are carried out on 5-years of historical data, not all precipitation variability has been accounted for. In addition, future changes are not taken into account.

Heat exchange with the tank has been suggested as a possibility for the system in design documents (Pedersen, 2020). This has not been investigated in this thesis and should be investigated by specialists within the subject.

Before any reuse water implementation is carried out, the water quality should be assessed more closely. The quality is likely good enough for non-potable usages, but as the tank receives water from a parking lot, the quality could vary.

6 Conclusion

The ZEB-stormwater management system represents a combined stormwater detention and reuse facility. In this thesis, the performance of the ZEB-pilot has been monitored and the system has been modeled for analysis on stormwater detention potential and reuse capacity.

The analysis of the systems stormwater detention performance during the monitoring period was limited based on an initial wrongful configuration of the orifice outlet in the tank. This configuration made the tank stormwater detention limited for a large part of the monitoring period. In addition, leakage from the tank was discovered. The leakage does not affect the detention potential of the system but will reduce the reuse capacity if not fixed.

Model simulation results on design events indicate that the system effectively handles high precipitation events. The system is predicted to handle events up to a 200-year return period. The ZEB-roof and parking lot provide fast runoff to the tank, while the LID-control drain pipes provide slower runoff. The overflow pipe from two bioretention cells will provide runoff in scenarios where the cells are fully saturated. The time this will occur is uncertain and may impact the performance in high precipitation events. Model simulation on 5-year historic precipitation data also show that the system will be able to provide the needed detention.

Simulations on the capacity of water available for reuse indicate that the tank can deliver 400 l/day with 100% coverage with the design outlet configuration. However, if it is acceptable that water will not be available at all times, the tank is predicted to provide up to 2000 l/day with above 70% coverage. A permanent increase in the outlet height will increase the reuse capacity. Even so, water will likely still not be available at all time. This implies that the variability in rainfall is an important factor for reuse capacity.

Implementations for the reuse segment in the ZEB-tank are currently not decided. Stakeholders must eventually decide what reuse purposes to implement. Although, outside uses like irrigation and bike washing seems like the most probable uses. Even so, the seasonal variation in these uses may limit the potential. Inside uses like toilet water may also be possible at the ZEB-laboratory, but may require expensive modifications. Simulations on probable toilet flushing demand suggest that the tank with the current configuration could provide a water coverage of 90%. For other similar systems, toilet usage should be considered early in the design process.

7 Further work

The ZEB-stormwater management system can be studied further. The monitoring period in this thesis was limited because of initial issues with the tank. To fully evaluate the stormwater control performance, longer monitoring periods are needed.

The model developed in this thesis has not been sufficiently calibrated or validated. To be able to perform a more extensive calibration of the model, each of the inflow pipes should be monitored. In addition to improve model performance, this can possibly lead to further analysis on bioretention and permeable pavement performance, as well as sub-catchment contribution. Further analysis on the bioretention cells and permeable pavement depend on whether more information about these can be obtained. In this thesis, the information obtained about the LID controls was limited.

Analysis of reuse could be performed when equipment for reuse is installed. Before reuse is implemented, a more detailed analysis of water demand should be performed. If more information on water demand for specific purposes is obtained, further scenarios could be performed with the model.

When looking further into stormwater reuse, the quality of the water could be analysed more closely. This can be used to determine if some sort of water treatment should be implemented before reuse. Seasonal variations of water quality may also possibly occur based on the parking lot stormwater.

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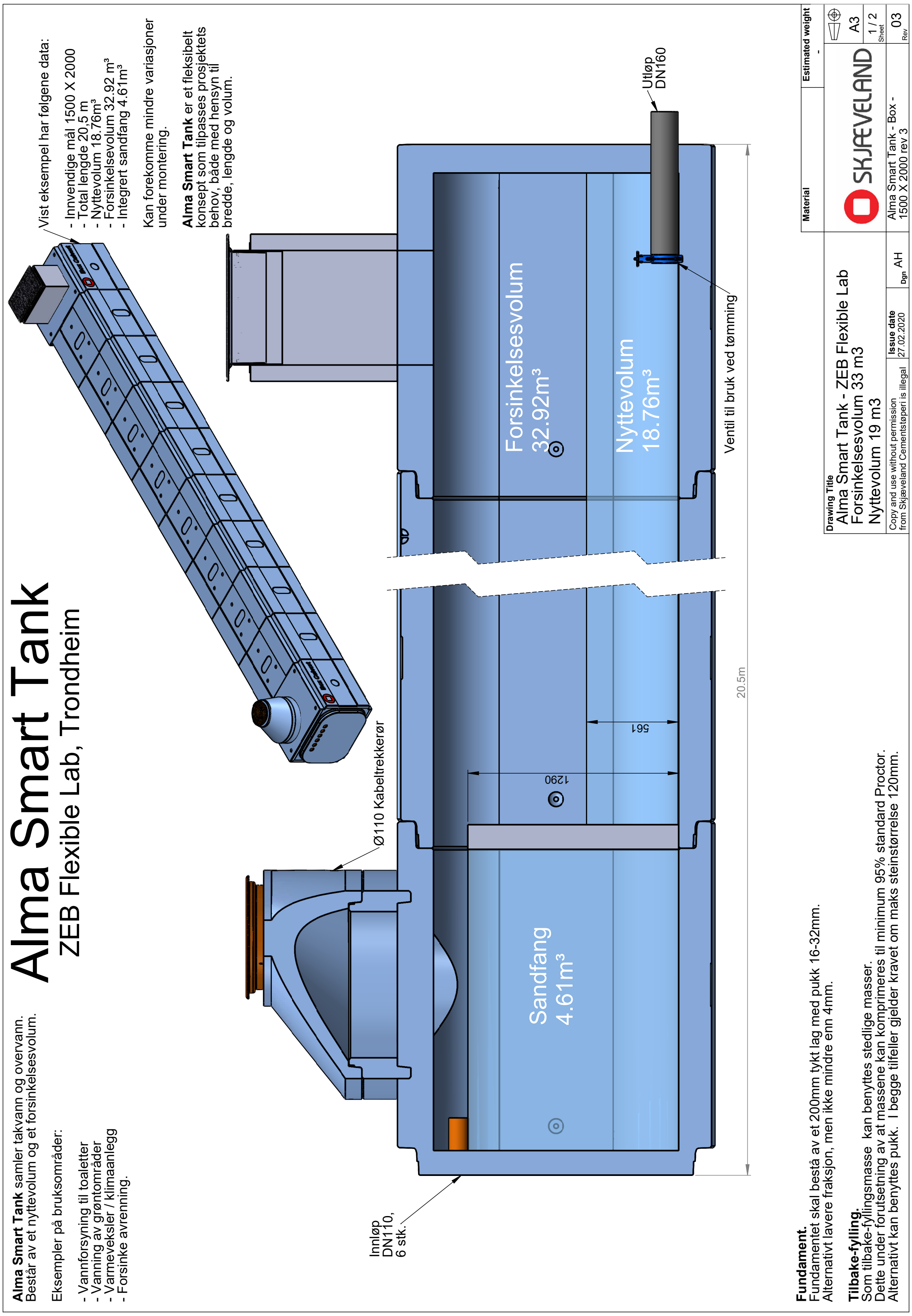
Appendices

Appendix A - Alma Smart Tank - ZEB Flexible Lab, Trondheim



Appendix B - Alma Smart Tank - Inlet and outlet configuration

Appendix C - SWMM LID parameter tables

The tables in this appendix show the parameters applied in SWMM for the rainfall-runoff module. Parameters are chosen mostly based on literature/reference values. The source of which the selection of each parameter is based on is shown below the table.

Rainfall-runoff module: Bioretention LID-control parameters

Layer	**Parameter**	**Bioretention cell number**		
		1	2	3
Bioretention surface area	A_{bio} (m^2)	$50^{(C)}$	$30^{(C)}$	$40^{(C)}$
Surface	Berm height (mm)	$2000^{(D)}$	$2000^{(D)}$	$2000^{(D)}$
	Vegetation volume (%)	$0.001^{(E)}$	$0.001^{(E)}$	$0.001^{(E)}$
	Surface roughness (Mannings n)	$0.0^{(B)}$	$0.0^{(B)}$	$0.0^{(B)}$
	Surface slope (%)	$0.0^{(B)}$	$0.0^{(B)}$	$0.0^{(B)}$
Soil	Thickness (mm)	$550^{(E)}$	$550^{(E)}$	$550^{(E)}$
	Porosity (volume fraction)	$0.52^{(A)}$	$0.52^{(A)}$	$0.52^{(A)}$
	Field capacity (volume fraction)	$0.15^{(A)}$	$0.15^{(A)}$	$0.15^{(A)}$
	Wilting point (volume fraction)	$0.08^{(A)}$	$0.08^{(A)}$	$0.08^{(A)}$
	Conductivity (mm/hour)	$80^{(A)}$	$80^{(A)}$	$80^{(A)}$
	Conductivity slope	$45^{(B)}$	$45^{(B)}$	$45^{(B)}$
	Suction head (mm)	$75^{(A)}$	$75^{(A)}$	$75^{(A)}$
Storage	Thickness (mm)	$150^{(E)}$	$150^{(E)}$	$150^{(E)}$
	Void ratio	$0.3^{(A)}$	$0.3^{(A)}$	$0.3^{(A)}$
	Seepage rate (mm/hour)	$0.001^{(E)}$	$0.001^{(E)}$	$0.001^{(E)}$
	Clogging factor	0	0	0
Drain	Flow coefficient	$1^{(E)}$	$100^{(E)}$	$100^{(E)}$
	Flow exponent	$0.5^{(B)}$	0	0
	Offset height (mm)	$13^{(E)}$	$600^{(E)}$	$600^{(E)}$

(A) SWMM5.org bioretention reference values (Dickinson, 2017a)

(B) SWMM Manual (Rossman, 2015)

(C) Measured

(D) Berm height set unrealistically high to ensure only the drain flow contributes to inflow

(E) Assumed

Rainfall-runoff module: Permeable pavement LID-control parameters

Layer	Parameter	Permeable pavement
Area (m^2)		642.7$^{(C)}$
Surface	Berm height (mm)	1.5$^{(A)}$
	Vegetation volume (%)	0.0$^{(B)}$
	Surface roughness (Mannings n)	0.012$^{(D)}$
	Surface slope (%)	0.05$^{(D)}$
Pavement	Thickness (mm)	70$^{(C)}$
	Void ratio (voids/solids)	0.072$^{(C)}$
	Impervious surface (fraction)	0$^{(B)}$
	Permeability (mm/hr)	3500$^{(A,D)}$
	Clogging factor	0
	Regeneration interval (days)	0
	Regeneration fraction	0
Soil	Thickness (mm)	180$^{(C)}$
	Porosity (volume fraction)	0.25$^{(A)}$
	Field capacity (volume fraction)	0.2$^{(A)}$
	Wilting point (volume fraction)	0.075$^{(A)}$
	Conductivity (mm/hr)	250$^{(D)}$
	Conductivity slope	45$^{(B)}$
	Suction head (mm)	75$^{(D)}$
Storage	Thickness (mm)	300$^{(C)}$
	Void ratio	0.3$^{(A)}$
	Seepage rate (mm/hour)	0.001$^{(D)}$
	Clogging factor	0
Drain	Flow coefficient	0.5$^{(D)}$
	Flow exponent	0.5$^{(B)}$
	Offset height (mm)	13$^{(D)}$

(A) SWMM5.org permeable pavement reference values (Dickinson, 2017b)

(B) SWMM Manual (Rossman, 2015)

(C) Information from construction (Pedersen, 2021)

(D) Assumed

Appendix D - Python script: Behaviour storage module

Author: Eirik Kjellsen

Method: Iterative level-pool routing

[ ]:
```
#For a new simulation: Set desired time-step (dt),
#    choose if demand is to be included, set input file names
```

[ ]:
```
#Import packages
import numpy as np
from scipy.optimize import minimize
from math import sqrt
from pyswmm import Simulation, Nodes, RainGages
```

[ ]:
```
#Set initial values

DEMAND = 'NO'                                  #If demand included, type 'YES'
SWMM_file = '.\SWMM-input.inp'                 #Name of SWMM .inp file
demand_file = 'Demand.csv'                     #Demand file(date;time;demand (l/s))

area = 35.6                                    #Area bottom of tank (m2)
dt = 60*5                                      #Timestep (second*minutes)
initial_wl = 0.558                             #Initial water level (m)
initial_storage = area*initial_wl*1000         #initial storage (l)
max_wl = 1.5                                   #Maximum water level (m)


#Set outlet values for orifice outlet
outlet_threshold = 0.558                       #Height of outlet (m)
outlet_A0 = 0.002                              #Area of outlet opening (m2)
Outlet_C = 0.7                                 #Outlet coefficient
g = 9.81                                       #Gravity

#Set leakage factor
leakage_factor = 0.001                         #Constant leakage (l/s) when H>0
```

[ ]:
```
#Get inflow data from SWMM model with pySWMM
inflow = []
date= []
precipitation = []
with Simulation(f'{SWMM_file}') as sim:
    rg1 = RainGages(sim)["Gage1"]
    node_object = Nodes(sim)
    #Out1 node instantiation
    Out1 = node_object["Out1"]
    #Set timestep
    sim.step_advance(dt)
```

```
    #Step through a simulation
    for step in sim:
        precipitation.append(rg1.total_precip)
        date.append(sim.current_time)
        inflow.append(Out1.total_inflow)

#Include demand-series or set demand to 0 for each time-step
if DEMAND =='YES':
    demand = np.genfromtxt(demand_file,delimiter=';',usecols=[2],unpack=True)
else:
    demand = [0 for i in range(len(date))]
```

[ ]:
```
#Functions

#Average inflow (IM =(i1+i2)/2)
def IM(inflow_t0,inflow_t1):
    Im = (float(inflow_t0) + float(inflow_t1))/2
    return Im

#Release curve (discharge based on water level, demand and leakage)
def release(H,i): # Outflow in l/s
    if H > outlet_threshold:
        orifice = Outlet_C*outlet_A0*sqrt(2*g*(H-outlet_threshold))*1000
        demand_t  = demand[i]
        release = orifice + demand_t + leakage_factor
    elif (H*area*1000)>((demand[i]+leakage_factor)*dt+1000):
        demand_t  = demand[i]
        release = demand_t + leakage_factor
    #If demand can not be met, no demand is withdrawn
    elif (H*area*1000)>((leakage_factor*dt)+500):
        release = leakage_factor
    else:
        release = 0.00000001
    return release


#Storage calculation
def storage(prev_storage,prev_release, Im, guess_Q):
    storage = max(0,prev_storage+(Im*dt)-((prev_release+guess_Q)/2*dt))
    return storage

#Function for water level based on storage volume
def water_level(storage):
    water_lv = float(storage)/(area*1000)
    return water_lv
```

```
#Difference to be minimized in optimizer
def diff(guess_Q,prev_storage,prev_release, Im,i):
    Q_out = release(water_level(storage(prev_storage,
                                        prev_release, Im, guess_Q)),i)
    diff =  Q_out - guess_Q
    return abs(diff)


#Scipy optimizer to find discharge iteratively
def optimizer(guess_Q,prev_storage,prev_release, Im,i):
    #Optimize diff by changing guess_Q
    res = minimize(diff, guess_Q, args=(prev_storage,prev_release, Im,i),
                   method='nelder-mead', options={'xatol': 1e-08, 'disp': False})
    #return updated guess Q
    return res.x[0]
```

[ ]:

```
#Initiate arrays
S = np.zeros(len(date))
wl = np.zeros(len(date))
Q_out = np.zeros(len(date))

#Set initial values
wl[0] = initial_wl
S[0] = initial_storage
Q_out[0] = release(wl[0],0)

#initialize value for demand not met
demand_not_met = 0
```

[ ]:

```
#Main function performs calculations for each timestep
def main():
    global demand_not_met
    for i in range(1,len(date)):
        Im = IM(inflow[i-1],inflow[i])
        guess_Q = Q_out[i-1]
        Q_out[i] = optimizer(guess_Q,S[i-1],Q_out[i-1], Im,i)
        #Register demand that has not been met
        if Q_out[i] <(demand[i]):
            print ('demand not met: Date/time ',date[i])
            demand_not_met += (demand[i]*dt)
        S[i]= storage(S[i-1],Q_out[i-1], Im, Q_out[i])
        wl[i] = water_level(S[i])
        if wl[i]>max_wl:
            print ('Overflow occured: Date/time ',date[i])
    #Returns arrays for water level, storage and discharge
    return wl,S,Q_out
```

```python
#Save water level, storage and discharge for time-period
wl,S,Qout = main()
```

[ ]:
```python
#Print out results from the simulation
print('Results from simulation: \n')

#print max and min water level values
print('Highest water level: ',max(wl), 'm')
print('Lowest water level: ',min(wl), 'm')
print('Maximum discharge: ',max(Qout), 'l/s','\n')

#Analyse peak of short term events
if len(date)<500:
    index_inflow_peak = inflow.index(max(inflow))
    index_max_discharge = np.where(Qout == (max(Qout)))
    print(f'Peak inflow occured: {date[index_inflow_peak]}')
    print(f'Peak outflow and max water level occured:
          {date[index_max_discharge[0][0]]}')

#Calculate and print demand results
if DEMAND=='YES':
    demand_coverage = (((sum(demand)*dt)-demand_not_met)
                       /(sum(demand)*dt))*100
    print('Total demand for time-period: ',sum(demand)*dt,'l')
    print('Number of days: ',(len(date)*(dt/60))/(60*24))
    print('Average demand per. day: ',(sum(demand)*dt)
          /((len(date)*(dt/60))/(60*24)),'l/d')
    print('Total demand not met for time-period: ',demand_not_met,'l')
    print('Demand coverage (%): ',demand_coverage)
```

Appendix E - Python script: Behaviour storage module - Irrigation modification

Author: Eirik Kjellsen

Description: Modification of the "release"-function in the behaviour storage module to simulate irrigation

[ ]:
```
#Demand (irrigation) is set as a constant value in l/s

#Code is based on time-steps of 10 minutes

def release(H,i):
    if H > outlet_threshold:
        orifice = Outlet_C*outlet_A0*sqrt(2*g*(H-outlet_threshold))*1000
        #Check if irrigation should be implemented
        if (date[i].month in (6,7,8)) and
        (sum(precipitation[(i-(6*24*3)):i]) == 0):
            release = orifice + demand + leakage_factor
        else:
            release = orifice + leakage_factor
    #Check if the tank has sufficient amounts of water to meet demand
    elif H*area*1000>((demand+leakage_factor)*dt+1000):
        #Check if irrigation should be implemented
        if (date[i].month in (6,7,8)) and
        (sum(precipitation[(i-(6*24*3)):i]) == 0):
            release = demand + leakage_factor
        else: release = leakage_factor
    #If demand can not be met, no demand is withdrawn
    elif H*area*1000>(leakage_factor*dt):
        release = leakage_factor
    else:
        release = 0
    #release in l/s
    return release
```

Appendix F - Python script: Input data SWMM

Author: Eirik Kjellsen

Description: Conversion of precipitation and temperature data to the format required by SWMM

[ ]:
```
##Open and get input values from the inputfile for temperature
filename = 'ris_precip_5year.csv'
infile = open(filename, 'r')
lines = infile.readlines()
infile.close()
##
```

[ ]:
```
#Create a output file that match SWMM time series file format

#Creating a output file
outfile = open("Risvollan-precip-10min_01.01.16-31.12.20.dat", 'w')

#Go through line by line. Skip the first line, which is the information
for line in lines[1:]:
    #get rid of trailing newline characters at the end of the line
    old_line = line.strip()
    #Separate line into a list of items.
    old_line = old_line.split(';')
    #Based on the location in input file, save date and time
    year = old_line[0][6:10]
    month = old_line[0][3:5]
    day = old_line[0][0:2]
    time = old_line[0][11:16]
    #Put together a new date string
    new_string = month+'/'+day+'/'+year+' '+time
    #Create a new list with date/time
    new_line = [new_string]
    #Insert 0 mm precip if value is missing
    if old_line[-1]=='-9999':
        new_line.append(str(round(float(0),2)))
    else:
        #Add the precipitation data
        new_line.append(str(round(float(old_line[-1]),2)))
    #Convert to string
    sline2 = ' '.join(new_line)
    #Write string to file
    outfile.write(str(sline2))
    #Change line
    outfile.write('\n')

#Close file
outfile.close()
```

[ ]:
```python
##Open and get input values from the inputfile for climatology
filename = 'ris_temp_5year.csv'
infile2 = open(filename, 'r')
lines2 = infile2.readlines()
infile2.close()
##
```

[ ]:
```python
#Create a output file that match SWMM climatology file format

#"Make line"-function put together a line of the correct format
def make_line(daily_temp,year,month,current_day):
    #Handle exception if no temperature data exist for entire day
    if not daily_temp:
        max_temp_day = '*'
        min_temp_day = '*'
    else:
        max_temp_day = str(max(daily_temp))
        min_temp_day = str(min(daily_temp))
    new_list = ['ZEB']
    new_list.append(year)
    new_list.append(month)
    new_list.append(current_day)
    new_list.append(max_temp_day)
    new_list.append(min_temp_day)
    #Wind speed
    new_list.append('*')
    #Evaporation
    new_list.append('*')
    sline2 = ' '.join(new_list)
    return sline2

#Create a output file
outfile = open("Risvollan-climate-file_01.01.16-31.12.20.dat", 'w')

#Initiate list for daily temperatures
daily_temp = []

#Go through line by line. Skip the first line, which is the information
for i in range(1,len(lines2)):
    #Remove trailing newline characters and split into list
    line = lines2[i].strip().split(';')
    if i ==1:
        current_day = line[0][8:10]
    day = line[0][8:10]
    if day == current_day:
        #Append if value exist
        if line[1]!='-9999':
```

```
            temp = float(line[1])
            daily_temp.append(temp)
        year = line[0][0:4]
        month = line[0][5:7]
    if day != current_day:
        #Make line and write to file
        sline2 = make_line(daily_temp,year,month,current_day)
        outfile.write(str(sline2))
        outfile.write('\n')
        #Initiate the next day
        current_day=day
        daily_temp = []
        #Append if value exist
        if line[1]!='-9999':
            temp = float(line[1])
            daily_temp.append(temp)

#Make line and write last day to file
sline2 = make_line(daily_temp,year,month,current_day)
outfile.write(str(sline2))

#Close file
outfile.close()
```

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