Høgskulen på Vestlandet

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An Analysis of Sewershed Inlet Ponding within the Alna River Catchment in Oslo, Norway

Melake Getabecha

Climate Change Management

Department of Environmental Sciences, Faculty of Engineering and Science at the Western Norway University of Applied Sciences

Thorben Dunse and Ashenafi Gragne

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Author: Melake Getabecha	Author sign.
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Abstract

The risks associated with urban flooding are increasing in response to global climate change, urbanization, and inadequate stormwater infrastructure. This rapidly increasing risk requires that cities across the globe respond through action geared at mitigating and adapting to changing hydrology of their surroundings. In order for this action to be effective, decision-makers need information that helps them understand, explain, and predict the current state of their urban hydrodynamics. This study focuses on improving the accuracy of the Alna Catchment System's Stormwater Management Model (SWMM), based in Oslo, Norway, by adding ponding data and assessing the impacts this data has on the model. Ponding data is acquired using a Geographic Information System (GIS) based terrain analysis which measures the potential ponding capacity surround each stormsewer inlet within the study are. The results revealed that 4% of the stormsewer inlets have ponding capacity of varying sizes and when their location and dimensions are entered into the model, they have a substantial impact on modeling results. Of the 9 different rain scenarios the model was run under, 4 scenarios saw a 100% reduction in Flood Loss (i.e. rain-based runoff whose end destination was undetermined) when ponding data was entered. The ponds were determined to have the highest impact in reducing Flood Loss during rain scenarios with return periods of 2-years, and 20-years, and durations of 20 minutes as well as scenarios with 200-year return periods and durations of 60 minutes and 1440 minutes. The addition of ponding data also resulted in an increase in modeled nodes experiencing flooding for all 9 rain scenarios and less Total Flooding Volume for 8 of the scenarios. The GIS-based terrain analysis proved an effective method to identify potential inlet ponds, and the addition of ponding data provided an increased understanding of how inlet ponding impacts the Alna Hydrological System.

Samandrag på norsk

Risikoen forbundet med byflom øker som svar på globale klimaendringer, urbanisering og utilstrekkelig overvannsinfrastruktur. Denne raskt økende risikoen krever at byer over hele verden reagerer gjennom tiltak rettet mot å redusere og tilpasse seg endret hydrologi i omgivelsene. For at denne handlingen skal være effektiv, trenger beslutningstakere informasjon som hjelper dem å forstå, forklare og forutsi den nåværende tilstanden til deres urbane hydrodynamikk. Denne studien fokuserer på å forbedre nøyaktigheten til Alna Catchment Systems Stormwater Management Model (SWMM), basert i Oslo, Norge, ved å legge til bunndata og vurdere innvirkningen disse dataene har på modellen. Damningsdata er innhentet ved hjelp av et geografisk informasjonssystem (GIS) basert på terrenganalyse som måler den potensielle damningskapasiteten som omgir hvert stormkloakkinnløp i studien. Resultatene avslørte at 4 % av stormkloakkinnløpene har tjernkapasitet av varierende størrelse, og når deres plassering og dimensjoner legges inn i modellen, har de en betydelig innvirkning på modelleringsresultatene. Av de 9 forskjellige regnscenarioene modellen ble kjørt under, så 4 scenarier en 100 % reduksjon i flomtap (dvs. regnbasert avrenning hvis endemål var ubestemt) når gruvedata ble lagt inn. Dammene ble bestemt til å ha størst innvirkning på å redusere flomtap under regnscenarier med returperioder på 2 år og 20 år, og varigheter på 20 minutter, samt scenarier med 200 års returperioder og varigheter på 60 minutter og 1440 minutter. Tillegget av damningsdata resulterte også i en økning i modellerte noder som opplever flom for alle 9 regnscenarier og mindre totalt flomvolum for 8 av scenariene. Den GIS-baserte terrenganalysen viste seg å være en effektiv metode for å identifisere potensielle innløpsdammer, og tillegg av damdata ga en økt forståelse av hvordan innløpsdammer påvirker Alnas hydrologiske system.

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1 Introduction

1.1 Urban Flooding

The inundation of land or property in a densely populated built environments, due to rainfall overwhelming drainage systems, also known as *urban flooding*, is an increasingly urgent and evolving risk currently faced by cities around the world (George M. Hornberger, 2014; O'Donnell & Thorne, 2020). The main culprit behind urban flooding is stormwater runoff, which is water that falls as precipitation and, rather than be absorbed by the landscape, stays on the surface, and collects or runs off to other areas that become inundated with water(O'Donnell & Thorne, 2020).

1.2 Driving Forces of Urban Flooding

Urban population growth, climate change, and insufficient infrastructure are some of the leading factors behind the rapidly changing hydrology of urban areas and the resulting flooding that occurs (George M. Hornberger, 2014; IPCC, 2022, pp. 24-25). Without a means to understand, explain, and predict the hydrology of urban areas, cities cannot effectively mitigate or adapt to the impacts of these driving forces which leaves them vulnerable to more flooding and the subsequent risks to human health, environmental health, and infrastructural integrity.

1.2.1 Climate Change

The Sixth *IPCC Assessment Report* from the Intergovernmental Panel on Climate Change emphasizes these urban flooding events as a significant impact and risk associated with climate change (IPCC, 2022). As global temperatures warm in response to greenhouse gas emissions, the atmosphere becomes capable of holding more moisture and weather patterns begin to change which, for many cities, results in more frequent and intense extreme precipitation events and more frequent and intense urban flooding (Hoegh-Guldberg, 2018). Warmer temperatures can also result in precipitation falling more frequently as rain rather than snow, and since warm air can carry more moisture than cold air, these precipitation events are likely to be more intense, dropping a lot of rain in a short amount of time (Benestad et al., 2022).

1.2.2 Urbanization

An increasing urban population is another driving force behind increasing urban flood risk (O'Donnell & Thorne, 2020). Currently people who live in cities represent approximately 55 percent of the global population. A number that is estimated to increase to 68 percent by the year 2050 (UN, 2019).

Urban population growth leads to increased urban development and land transformation which can increase impervious areas due to the transformation of land from agricultural or natural landscapes to buildings and roads (Güneralp et al., 2015). This increase in impervious area corresponds to more urban runoff because precipitation that falls as rain, snow or hail has less places to be absorbed by the landscape, evaporate or transpire and instead runs off buildings and streets until they enter a waterway or a stormwater system (Nirupama & Simonovic, 2007).

In addition to lower infiltration and evapotranspiration, this high level of impervious cover causes urban areas to have much shorter response times to precipitation events. Rain that falls on buildings and streets gather faster than they would in natural landscapes and as a result, urban catchments have high peak flows compared to less developed areas or natural landscapes as is visualized in Figure 1. Flooding occurs in response to these short response times and high peak flows because water gathers faster than it can be evapotranspired, absorbed by the ground, or evacuated by stormwater infrastructure (George M. Hornberger, 2014).

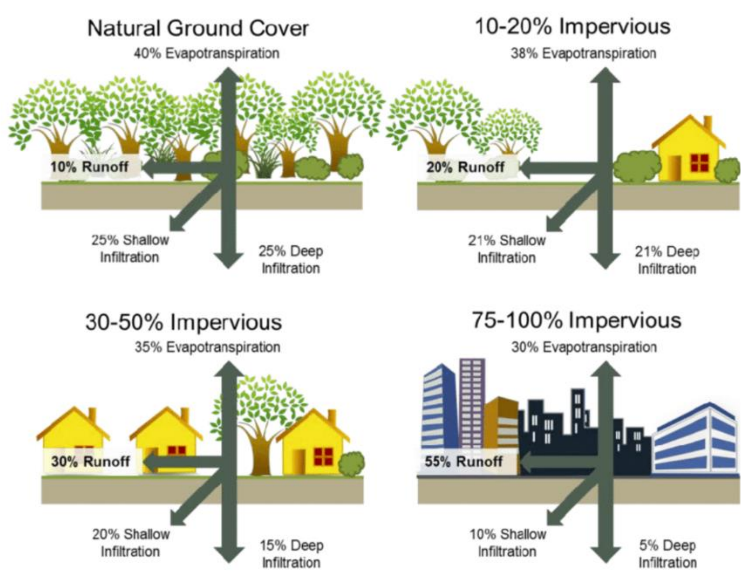


Figure 1: Effects of impervious surfaces on stormwater runoff, infiltration and evapotranspiration (Holt et al., 2018).

Several studies have linked the increase in impervious areas to an increase in urban flooding and as urban populations increase, and land is transformed, flooding is likely to increase (Ahiablame et al., 2013; Holt et al., 2018; Nirupama & Simonovic, 2007; Paule-Mercado et al., 2017).

1.2.3 Insufficient Stormwater Infrastructure

An increase in urban runoff could be somewhat mitigated by a robust and well-functioning stormwater system but, for many cities, stormwater systems are unable to take on the runoff they are currently facing. Inadequate stormwater infrastructure is in fact another driving force behind urban flooding in many cities across the globe (Lindholm, 2014; O'Donnell & Thorne, 2020). As urban populations have increased, their stormwater infrastructure has struggle to keep up with the growth to the point that they are regularly overwhelmed by the runoff they are faced with. This is due to both the increasing amount of stormwater runoff generated by urbanization and the lack of maintenance or ability to update stormwater infrastructure (Megen, 2018).

Thus, due to the crisis of climate change, a growing urban population, and inadequate stormwater infrastructure, urban flooding risk is likely to grow if mitigation and adaptation measure are not taken (EEA, 2017; IPCC, 2022).

1.2.1 The Growing Impact of Urban Flooding

The IPCC *Climate Change 2022: Impacts, Adaptation and Vulnerability* report identifies flooding as one of three main climate-related risks facing cities and the risk is growing (IPCC, 2022, p. 21). Even when disregarding climate change impacts (i.e. heavier and more frequent rain scenarios), studies have stated that urban flood hazards are expected to increase 2.7 times from 2000 to 2030 (Güneralp et al., 2015; IPCC, 2022). This present and growing risk requires the attention of cities to understand, mitigate and adapt to both present and future risks as well as their associated impacts. This study will focus on the first of the three, increasing understanding of flood risks.

Urban floods can occur in several forms such as fluvial (river overflow) floods, pluvial (precipitation-driven) floods and sewer overflow which can influence one another especially within the urban setting (Field C.B., 2012). For example, both fluvial and pluvial floods can overwhelm urban stormwater and sewage infrastructure, causing sewer overflows which in turn compound the risks associated with such flooding hazards.

In the past decades, there have been a variety of extreme flooding events that have caused excessive damage to infrastructure, the natural environment and human health in cities including Copenhagen (2010, 2011, 2014), Queensland (2010), Bangkok 2011 (Gale & Saunders, 2013) New York (2012), Nairobi (2015), and the French Riviera (2015) to mention a few.

Most recently, the European and Zhengzhou floods of 2021 demonstrated the devastating effect flooding can have on cities, countries, and regions. The European floods, which were focused mainly in Germany, cause over 200 fatalities throughout Germany, Austria, Belgium, Italy, and Romania in addition to an estimated cost of $13 billion making it the "the costliest individual insurance industry event on record in Germany, Belgium, and Luxembourg". The urban flooding in Zhengzhou was also listed as the "costliest weather event ever recorded for Chinese insurers" with an estimated cost of $19 billion (AON, 2021). The devastating impacts of floods like these seem to be growing and thus demand the attention of cities worldwide.

Additionally, cities tend to have more people and investments (i.e. infrastructure) in smaller areas compared to rural areas and thus the impacts of flooding tend to be more costly in urban areas. For example, the $19 billion cost of the 2021 Zhengzhou flood is an estimate for the region of Henin but the vast majority of the insurance claims filed were for damages within the city of Zhegnzhou (AON, 2021).

1.3 Tools for Understanding Urban Hydrology

As a tool to understand, explain and predict the hydrodynamics of urban areas, many cities, research institutes and companies have turned to Geographic Information Systems (GIS) and hydrological models.

GIS software and remote sensing technology are tools commonly used by planners, researchers and hydrologist interested in analysing spatial data. In the field of hydrology, GIS is often used for spatial analysis wherein the flow paths, ponding areas, and flood zones can be determined using digital terrain models (DTMs) of a given area (Abedin & Stephen, 2019; Chen et al., 2009).

Since the 1960s, the field of *hydrological modelling* has grown significantly in its abilities to approximate hydrological phenomenon. This is in large part due to advances in computational power and data collection (Rosbjerg & Rodda, 2019; Salvadore et al., 2015). These advances have encouraged the development of a wide variety hydrological models, a growing number of professionals who utilize these models and their results, and a growing population of stakeholders impacted by the decisions these models influence (Rosbjerg & Rodda, 2019).

The appropriate use and reliability of these models are still a topic of controversy and there is no consensus on an industry standard model for urban catchment modelling. Urban hydrology is particularly difficult to model due to the interaction of both the built elements (e.g. curbs, pipes and buildings) and natural elements (e.g. grass and trees) of urban areas (Niazi et al., 2017).

1.3.1 Stormwater Management Model

The Stormwater Management Model 5.2 (SWMM) is the latest version of one such hydrological model produced by the United States Environmental Protection Agency (US EPA). SWMM 5.2 is a dynamic rainfall-runoff distributed model with the capability to simulate both continuous and single precipitation events and their associated impacts on runoff quality and quantity. The tool is widely used by professionals interested in simulating urban hydrology as it is structured to simulate urban areas (Niazi et al., 2017). It incorporates both surface runoff and water that travels through pipes, channels, treatment devices, pumps and regulators which make it ideal tool for planning, designing, and assessing existing and potential stormwater infrastructure such as combine storm and sanitary sewers, detention and retention ponds, and green roofs (EPA, n.d.).

The software can measure flow rate, flow depth, and quality of water for individual subcatchments, pipes and channels and can identify which subcatchments flood and for how long under simulated circumstances. The capabilities and typical applications of SWMM 5.2 are vast and are summarised in Table 1.

Table 1: Capabilities and typical applications of the EPA SWMM 5.2 Hydrological Model taken from the manual (EPA, n.d.)

Runoff and Precipitation Generation Processes	Runoff and Precipitation Transport Processes	Resulting runoff and pollutant loads	Typical Applications
- time-varying rainfall - evaporation of standing surface water - snow accumulation and melting - rainfall interception from depression storage - infiltration of rainfall into unsaturated soil layers - percolation of infiltrated water into groundwater layers - interflow between groundwater and the drainage system - nonlinear reservoir routing of overland flow - rainfall-dependent infiltration and inflow (RDII) for sanitary sewersheds - capture and retention of rainfall/runoff with various types of low impact development (LID) practices.	- standard closed and open conduit shapes as well as natural channels routing - special elements such as storage/treatment units, curb and gutter inlets, culverts, flow dividers, pumps, weirs, and orifices - external flows and water quality inputs from surface runoff, groundwater interflow, rainfall-dependent infiltration and inflow, dry weather sanitary flow, and user-defined inflows - kinematic wave or full dynamic wave flow routing methods - various flow regimes, such as backwater, surcharging, reverse flow, and surface ponding - user-defined dynamic control rules to simulate the operation of pumps, orifice openings, and weir crest levels	- dry-weather pollutant buildup over different land uses - pollutant washoff from specific land uses during storm events - direct contribution of rainfall deposition - reduction in dry-weather buildup due to street cleaning - reduction in washoff load due to BMPs - entry of dry weather sanitary flows and user-specified external inflows at any point in the drainage system - routing of water quality constituents through the drainage system - reduction in constituent concentration through treatment in storage units or by natural processes in pipes and channels.	- design and sizing of drainage system components for flood control - sizing of detention facilities and their appurtenances for flood control and water quality protection - flood plain mapping of natural channel systems - designing control strategies for minimizing combined sewer overflows - evaluating the impact of rainfall-dependent infiltration and inflow on sanitary sewer overflows - generating non-point source pollutant loadings for waste load allocation studies - evaluating the effectiveness of BMPs for reducing wet weather pollutant loadings.

1.4 Stormwater Management in Oslo, Norway

In Oslo, Norway, city employees are utilizing the SWMM 5.2 model as a mitigation and adaptation tool as they contend with the increasing risks of urban flooded mentioned above. This study is focusing on a particular area within the City of Oslo, the Alna Catchment System, and aims to improve upon the SWMM model the city is currently utilizing to represent this catchment and its hydrological system.

1.4.1 Flood Risk Drivers in Oslo

Oslo is located in south-eastern Norway, in an environment categorized as a “Boreal Region” by the European Environmental Agency (EEA). According to the EEA’s report on *Climate Change, Impacts and Vulnerability in Europe 2016*, the boreal regions are expected to experience more frequent and heavy precipitation events in the coming decades (EEA, 2017, p. 25). Precipitation recorders also indicate an increase in precipitation for Oslo over the last century. Figure 2 demonstrates this increase in annual precipitation from 1901 to 2020 as well as the predicted annual precipitation when the climate forcing conditions of Representative Concentration Pathway 8.5 are taken into account (World Bank Group, 2022). These trends emphasize the pattern of increasing precipitation and thus a potentially higher risk of flooding within the city.

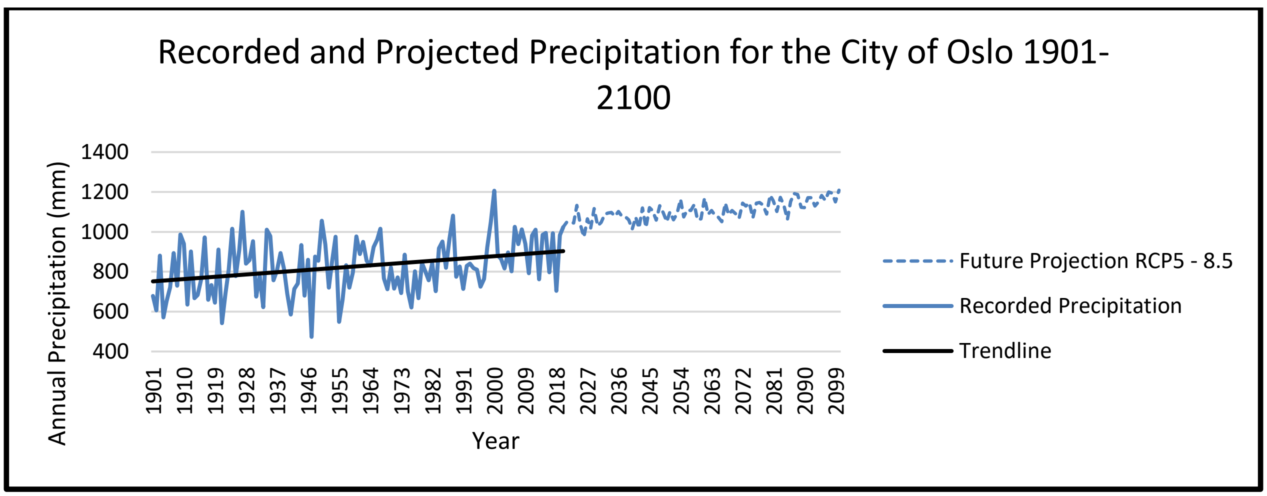


Figure 2: Annual Precipitation records from 1901 to 2020 for the City of Oslo and annual precipitation projections taken from RPC 8.5 from 2021-2100. Data sourced from the World Bank Group Climate Change Knowledge Portal (World Bank Group, 2022).

Since 1990 Oslo’s population has grown by 153 percent, from roughly 458,000 to 699,000 inhabitants, and all the districts included in the Alna catchment have experience significant population growth in response (SSB, 2022). This growth in population raises flood risks since more people are exposed to the more frequent and heavy precipitation events (O'Donnell & Thorne, 2020).

In the Alna catchment, urban flood risk is also influenced by the infrastructure that exists throughout the catchment. The urbanization and the piping and covering of tributaries in the catchment have resulted in fast response times and high velocity discharges into the main river. Additionally, the catchment has high flood peaks during extreme storm events resulting in the areas near the river being at risk of flooding (NIVA, 2020). The piped or covered tributaries also suffer from faulty pipe connections resulting in possible stormwater contamination from sewage and water from contaminated grounds.

Additionally, the stormwater infrastructure put in place decades ago are not designed to take on the growing amount of runoff and sewage being produced by the urban expansion and population growth of the last several decades (NIVA, 2020). This mismatch of stormwater infrastructure capacity and impervious urban areas was a large contributor to the 2015 Alna flood and is central to the mitigation and adaptation measures needed to reduce flood risk (A. S. Gragne, 2015; City of Oslo, 2016; NIVA, 2020).

1.4.2 Risks of Sewer Overflow

These flooding events present a risk to public health, environmental health, and economic stability in the area, in part due to the setup of the stormwater system. Alna’s stormwater system consists of stormsewer (pipes that carry stormwater from one area of the city to another), sanitary sewers (pipes that carry sewage and other waste from homes, businesses and other facilities to water treatment sights) and combine sewers (pipes that carry a mixture of stormwater and sewage to treatment sites).

During a flood event, if the sewer systems are overwhelmed the contents of these sewers can overflow and poor out of manholes or inlets flooding the streets with both stormwater and sewage (i.e. sewer overflow). This poses both public health concerns for residents who come in contact with the sewer overflow, property owners whose property can be damaged by the excess water, and to the marine and riparian environment which can be contaminated by the contents of the overflow (Dittmer et al., 2020; Mallin et al., 2007).

Sewer overflow poses a particularly high risk in the Alna Catchment as the heavy urbanization, covered tributaries and faulty pipe connections have resulted in the Alna River being one of the most polluted rivers in Norway according to a 2018 report from the Norwegian Institute for Water Research (NIVA, 2018). All these risk factors demonstrate the need for mitigation and adaption which must be informed by the best information available.

1.4.3 Plans for Stormwater Management

In response to this risk, the city of Oslo's Water and Sewage Authority (VAV) along with other city agencies have developed mitigation and adaptation plans, many of which are currently underway. One such plan is the *Action Plan for Stormwater Management* which sets the direction for stormwater management in the City of Oslo (City of Oslo, 2016).

In the plan, the city acknowledges that pluvial flooding is becoming "more visible and more frequent than before… [and] areas that were not previously affected are also experiencing flooding more often". In response to this the city has set targets for stormwater solutions and five areas of focus which the city should prioritise (Table 2).

Table 2: Stormwater Management Targets and Focus Areas. Taken from the City of Oslo's Action Plan for Stormwater Management (City of Oslo, 2016)

Stormwater Management Targets	Areas of Focus
- **Damage caused by stormwater and urban flooding are avoided** - **All stormwater that is conveyed to a recipient is of a quality that can be handled by the recipient, so that targets specified in the water regulations are achieved** - **Stormwater is infiltrated, retained and used locally where practicable, using open and multifunctional retention networks.**	1. **Acquire more knowledge** 2. **Prevent negative impacts** 3. **Develop model projects** 4. **Establish closer working relationships** 5. **Improve information and guidance**

A central tactic the city is using to meet its goal of "floodway[s] and retention networks that work" is the 3-step strategy. The strategy, simply put, is to guide precipitation so it **(1) infiltrates after light rain**, (**2) is retained or detained for moderate rain scenarios**, and **(3) is safely guided to a recipients** (i.e. floodways) after heavy rains (Figure 3).

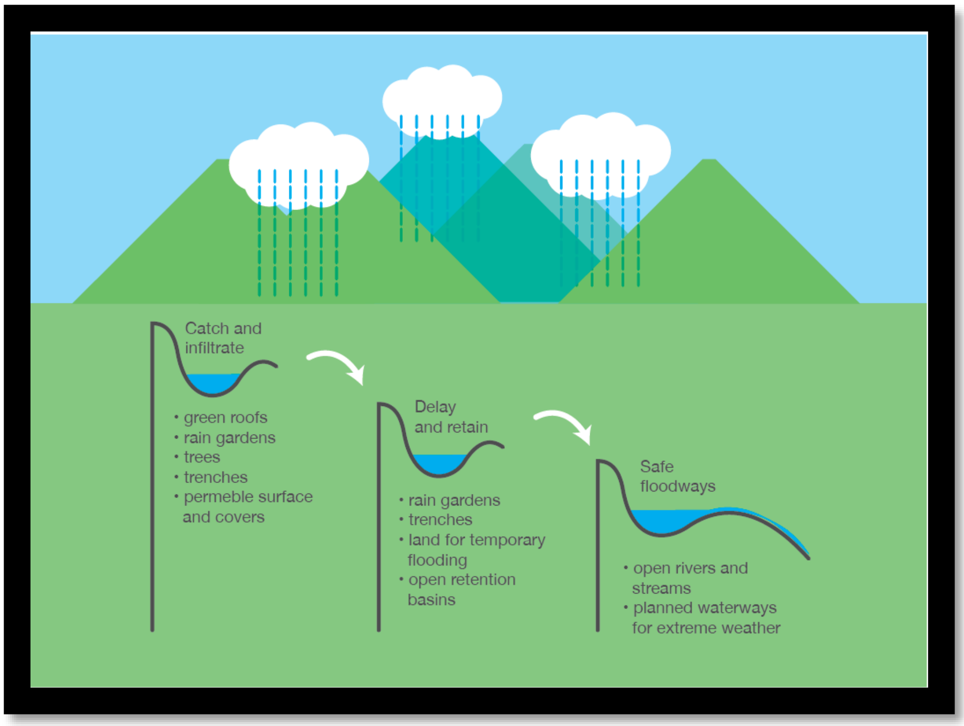


Figure 3: Visual representation of the three-step strategy and measures associated with each step. Taken from the City of Oslo's Action Plan for Stormwater Management (City of Oslo, 2016)

1.4.4 The Alna SWMM Model

A step the City of Oslo has taken to meet these goals is to build a hydrological model of the Alna Catchment and its associated sewersheds (an area henceforth referred to as the Alna Hydrological System) to better understand its hydrodynamics. This model has been modified by staff at the Norwegian Institute for Water Research, into a SWMM model and is henceforth referred to as the *Alna SWMM Model* or simply the *SWMM Model*.

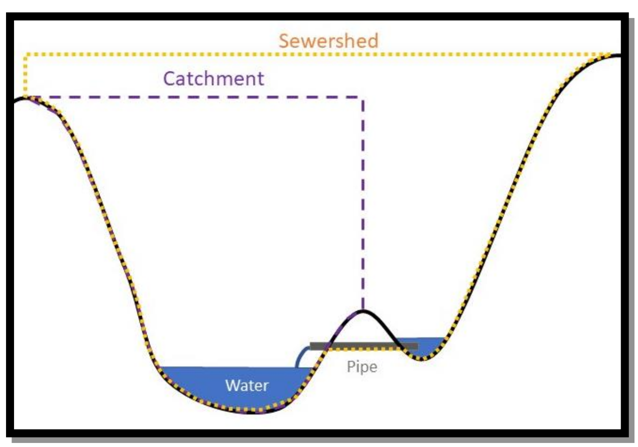


Figure 4: Sectional view a of catchment and sewershed. The sewershed extends further than the catchment boundaries due to the connecting pipe.

A *sewershed*, in this case, is the area where all water (guided either by topography or stormsewer pipes) flows to a single end point. Sewersheds tend to cover larger areas than catchments as the piped water is not constrained by surface topography as is demonstrated by Figure 4.

The Alna SWMM Model divides the catchment and associated areas into smaller sewersheds, wherein each sewershed has a designated stormsewer inlet Figure 5. The delineation of these sewersheds is further explained in the Methods section of this thesis. The SWMM Model simulates and measures both surface runoff and sewer flow to provide a comprehensive view of the Alna stormsewer and surface drainage system and how it may react to different rain scenarios. By doing so, the city is acting to fulfil its first area of focus “acquiring more knowledge” which in turn can help to meet the other goals and strategies it has laid out in its plan.

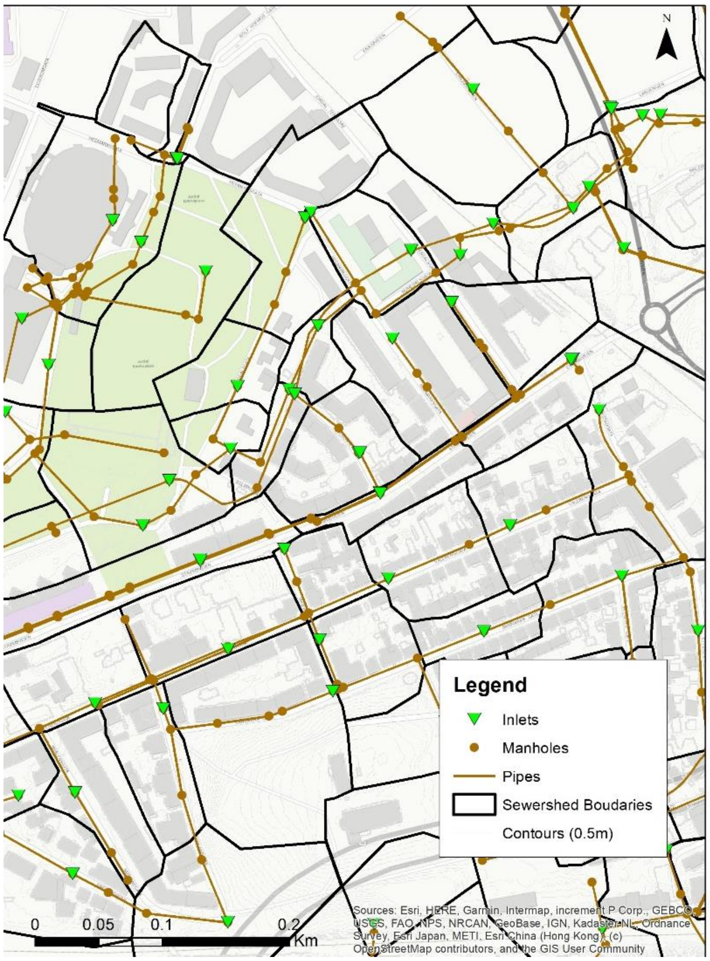


Figure 5: Map showing sewersheds and stormsewer network in the Alna Catchment System

Currently, the Alna SWMM Model uses a variety of inputs which include both terrain-based hydrology information (surface elevation and slope, sewershed location and area, and surface cover and permeability) and sub-terranean hydraulic infrastructure information (stormsewer and sewage pipe type, size, shape, slope, location and connection points, and inlet and outlet depth, shape, location and capacity). The model uses historical precipitation data to model representative rain scenarios ranging from a 2-year rain scenario to a 200-year rain scenario for durations ranging from 20 minutes to 1440 minutes. Further information on the model will be explained in the Methods section of this thesis.

1.4.1 Gap of Knowledge

Two inputs SWMM allows for, but are missing in the Alna SWMM Model, is *Ponded Area* and *Surcharge Depth*. These inputs are used in SWMM to determine how much water can be stored above stormsewer inlets once they have exceeded their capacity to evacuate runoff. If SWMM is run without the addition of ponds, than all excess runoff is disregarded as *Flooding Loss* (also called *Flood Loss* in this study) and its final destination is never determined. SWMM calculates that amount of water that becomes runoff but this water never returns into the modelled system once it is unable to enter an inlet. This leads to an inaccuracy in the mass balance equation of the model as more water is entering the system as rain than is leaving it, either through piped flow or runoff (Lewis A Rossman, 2022).

In a heavy rainfall situation, it is not uncommon for stormsewer inlets to exceed their capacity to evacuate runoff and overflow. Typically, the excess runoff either ponds around the inlet or continuing to runoff downhill which can have both positive and negative impacts. For example, ponding around an inlet can provide temporary storage (i.e. detention) of water providing temporary relief for downhill areas (step 2 of Oslo's 3-step plan) reducing peak flows. Additionally stormwater detention can allow for sediment and pollutants to settle out of the water as it slows down which also can reduce overall erosion. At the same time, ponding is essentially small-scale flooding and if ponds form in dense area (e.g. near sensitive infrastructure, vulnerable residents, busy roads, or contaminated sights) they could cause serious problems. For these reasons and more, the addition of ponding information could serve as a valuable insight in understanding they hydrodynamics of the Alna Hydrological System.

1.4.2 Aim of the Study

This study focuses primarily on the second and third steps of Oslo's 3-step strategy (retention and safe conveyance of runoff) and attempts to acquire more knowledge on the current state of the Alna Hydrological System by adding ponding data and improving upon the current Alna SWMM Model.

A GIS-based terrain analysis investigates where stormwater can be retained above stormwater inlets (i.e. pond) and how much water can be retained before it runs off to a neighbouring sewershed. The terrain analysis results are then added to the Alna SWMM Model and the model is run with and without ponding, in various rain scenarios, to determine the impact ponding has on the modelled hydrological system. Simply put, this study demonstrates a method to acquire ponding data and measure the impact this data has on the overall hydrological model.

The research questions of this study are:

1) **What is the inlet ponding capacity of each sewershed in the Alna Hydrological System?**
2) **What is the impact these potential ponds have when entered into the Alna SWMM Model?**

2 Methods

The methods of this thesis utilized GIS analysis and hydrological modelling to improve the current understanding of the hydrodynamics within the Alna Hydrological System. The current hydrological model used by the city of Oslo does not incorporate the ponding potential of each sewershed. By calculating the ponding potential of each sewershed and adding it to the hydrological model, city employees could gain a better understanding of the hydrodynamics of the system.

2.1 Study Area

The study focuses on the Alna Hydrological System which is an area surrounding the Alna River in Oslo, Norway (Figure 6). The Alna River is the longest river in Oslo stretching 15 km. The river begins in the northeast at Alnsjøen lake, travels down through the eastern Oslo and ends at Oslofjord in the Bjørvika neighbourhood in the Sentrum district. The catchment associated with the Alna River covers 69 km^2 and approximately two thirds of the area consist of urbanized area (NIVA, 2020).

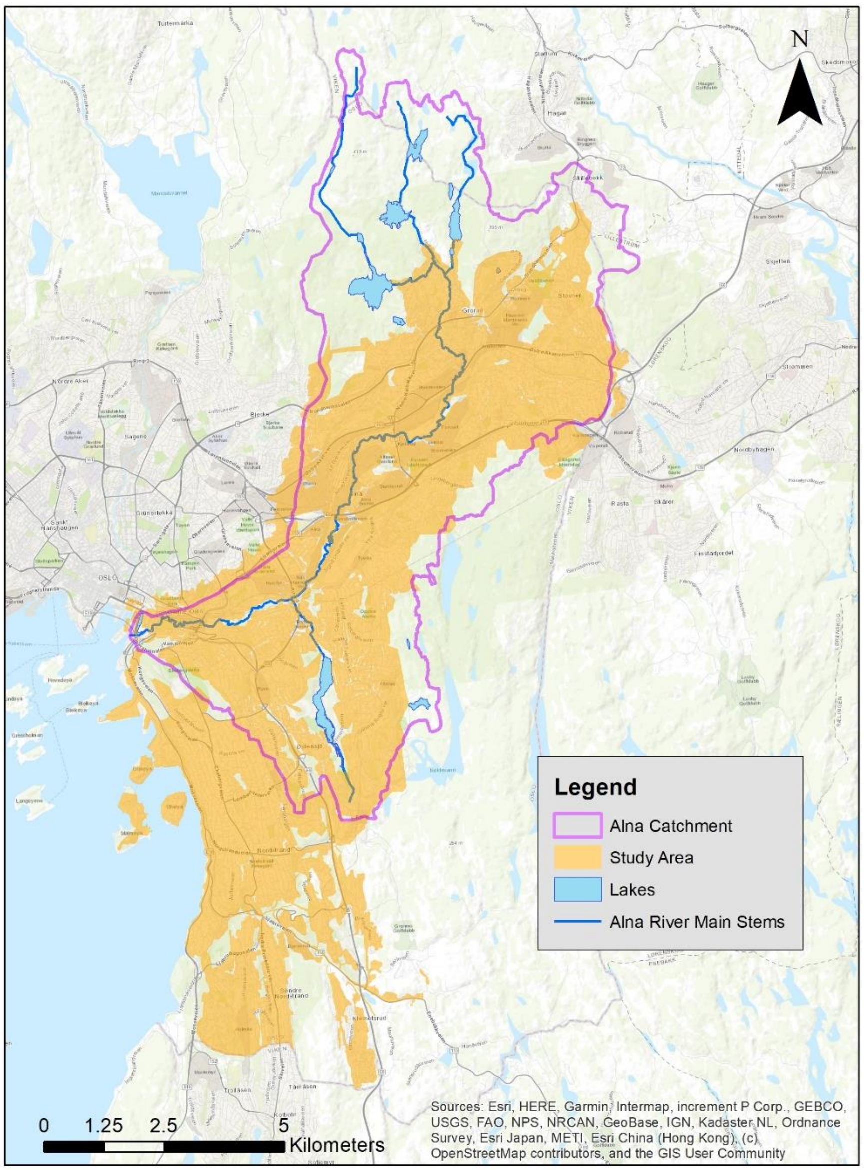


Figure 6: The Alna Hydrological System in relation to the Alna River and Catchment.

The full extend of the study area of this thesis extends beyond the Alna Catchment and was determined based on the extent of the current Alna SWMM Model which centres around the urban areas associated with the Alna River Catchment. It includes the urban areas of the Alna Catchment and areas outside the catchment which are connected via infrastructure such as pipes (**Error! Reference source not found.**).

The river has undergone a lot of development starting in 1922 when the lower section of the river was driven underground through piped system called the Kværnerbyen culvert. Following this, extensive urbanization and the installation of factories forced other sections of the river and its tributaries into underground pipes or culverts which resulted in approximately 80% of the river's tributaries to be covered or closed (NIVA, 2020).

The Alna catchment has experienced several flooding events in the recent decade, the most recent of which was in 2015 in the area surrounding the Kværnerbyen culvert (Gragne et al., 2015). Like many urban catchments, the driving forces behind these floods can be attributed to climatic factors, a growing urbanized area, and insufficient stormwater infrastructure.

The modelled area is subdivided into 7987 sewersheds of varying sizes and shapes, each of which have a designated stormsewer inlet. The determination of the size, shape and identification of the sewersheds were based on 8 criteria which guided the delineation. These criteria included but were not limited to:

- Limiting sewersheds to 1 km^2
- Minimizing the number of waterways that crossed sewersheds
- Placing sewershed boundaries on the side of roads as opposed to the middle of the road
- Ensuring sewershed boundaries do not cut through buildings

It is important to note that these criteria created sewersheds that do not act the same as drainage zones or subcatchments, and stormsewer inlets were not necessarily the lowest point in their associated sewershed. Additionally, all sewersheds did not meet all the criteria. For example, some sewersheds were larger than 1 km^2.

The inlets of each sewershed were designated by identifying all manholes in each sewershed and assigning one to be the stormsewer inlet, with the intent of minimizing pipe flow errors in the model. This resulted in many inlets being placed towards the centre of the sewershed rather than at the lowest elevation point as shown in Figure 8.

While there is no publicly available document detailing the creation of the Alna SWMM model, VAV employees were contacted via email and helped explain some of the factors that determined the location, shape, and size of sewersheds and their associated inlets (U. Zühlke & J. Kvitsjøen, personal communication, April 2022).

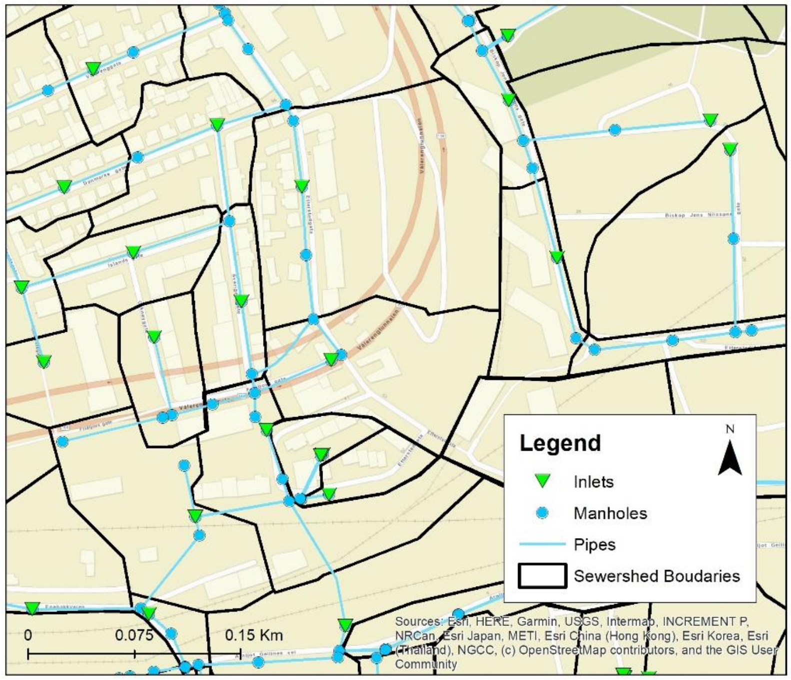


Figure 8:Inlet and manholes within Alna Catchment System.

The entire study area spans 105,420 km^2 with sewersheds area ranging from 0.07 km^2 to 695.00 km^2. The average sewershed size is 13.22 km^2 and most are situated in urban areas. Smaller sewersheds tend to be more centrally located within the study area, whereas the larger sewersheds tend to be on the outer edge, especially towards the southern edge (Figure 9).

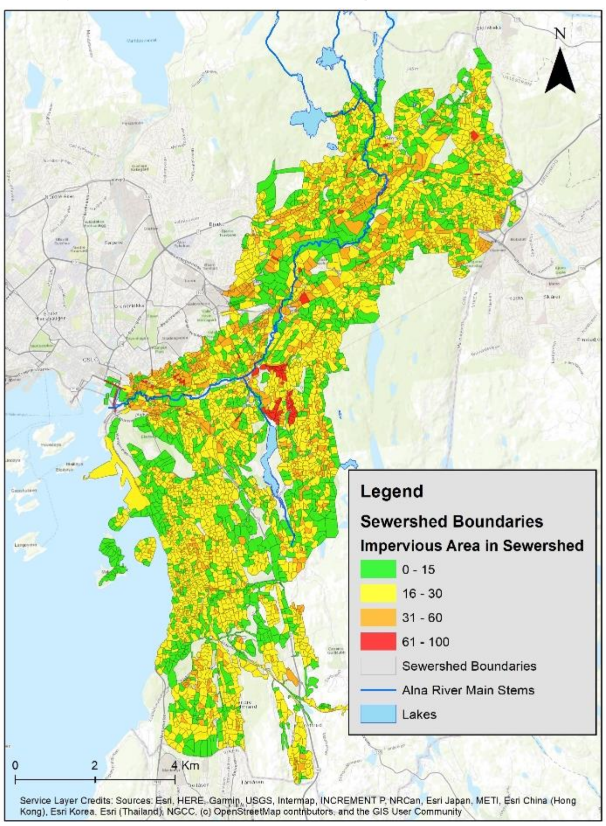


Figure 7: Impervious surface coverage for each sewershed.

According to the sewershed shapefiles provided by VAV, 20 percent of the study area is covered by impervious surfaces and on average, sewersheds have approximately 22 percent of their area covered by impervious surfaces. These impervious surfaces cover a higher percentage of sewersheds located in the interior of the study area with less impervious coverage for those sewersheds on the exterior, as is shown in Figure 7.

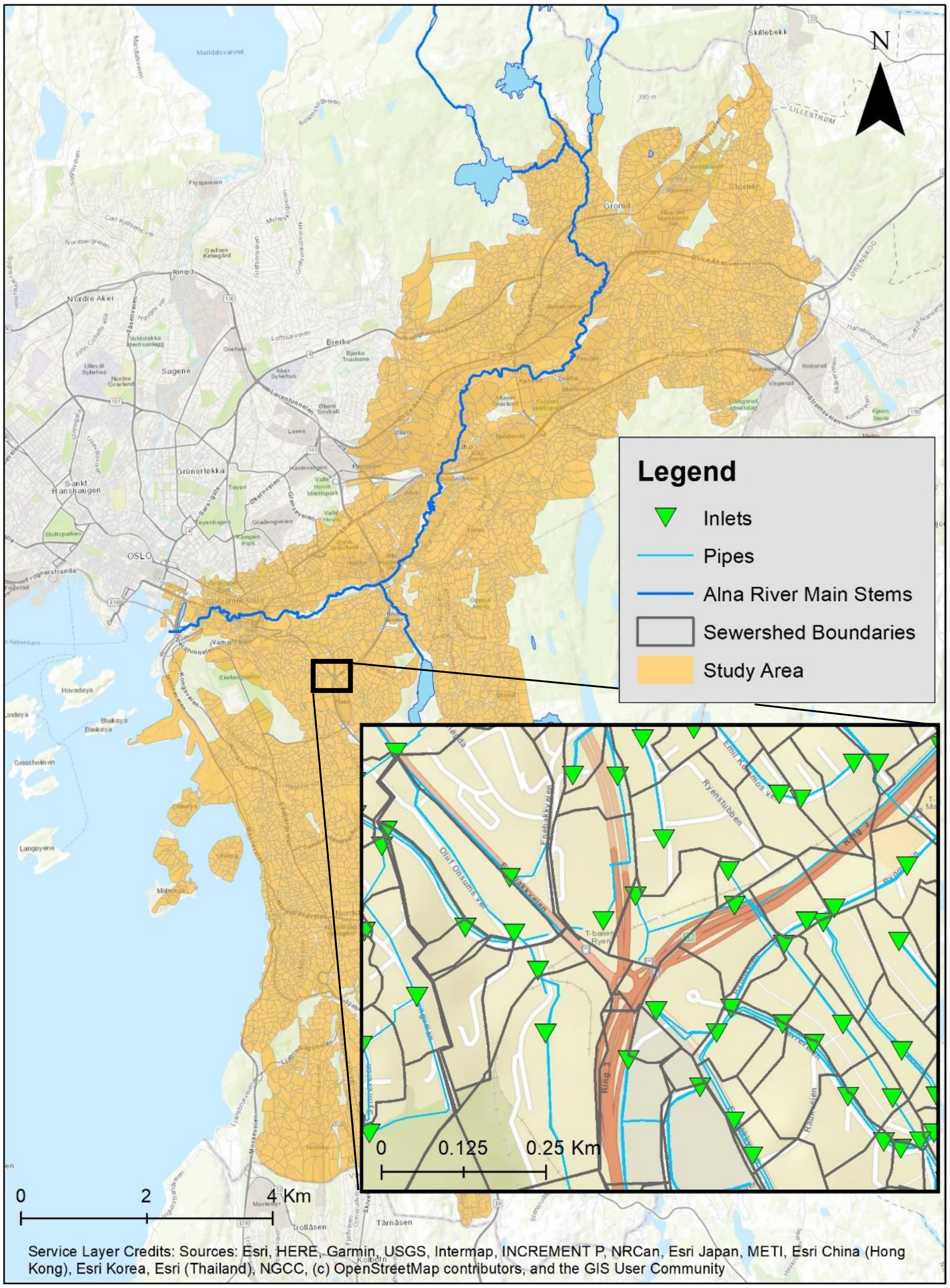


Figure 9: Study area with inset map of sewershed boundaries, inlets and pipes.

2.2 Terrain Analysis

The GIS-based terrain analysis was conducted using ArcMap 10.8.1 to determine the area and average depth of potential ponding sites within each sewershed.

2.2.1 Base Data Collection

The base data used in the terrain analysis, is displayed in Table 3 and included a 1-meter digital terrain model (DTM) downloaded from høydedata.no, a buildings shapefile from Geonorge.no, and sewershed boundary and inlet/manhole shapefiles obtained from the Norwegian Water and Sewage Authority (VAV) via the Norwegian Institute for Water Research (NIVA).

Høydata.no is a publicly available online databases managed by the Norwegian Mapping Authority (Kartverket). The 1-meter DTM was constructed from a laser scanning process which took place in 2019. The resulting point cloud was then turned into a DTM by Høydata.no using triangulation with natural neighbour interpolation. Geonorge.no is also a publicly accessible online database managed by Kartverket, however to download the buildings shapefile () a registered Geonorge account was required. Thus, a registered university account was used to collect the shapefile. The shapefile comes from FKB Bygning, a continuously updated dataset.

Table 3: Sources and details of acquisition for base data used in the GIS terrain analysis

Data	Source	Details
Digital Terrain Models (DTMs)	www.Høydedata.no	➢ 1-meter Oslo Laser Scanning 2019 downloaded from website. ➢ Downloaded January 27th, 2022 ➢ (Publicly accessible data)
Buildings Shapefile	www.Geonorge.no	➢ FKB Bygning Shapefile collected through university Geonorge account. ➢ Downloaded on January 27th, 2022 ➢ (Geonorge.no account required)
Sewershed and Stormwater Inlets	Oslo Water and Sewage Authority (VAV)	➢ Shapefiles requested by co-supervisor through NIVA. ➢ Received March 3rd, 2022 ➢ (Approval from VAV required)

2.2.2 Ponding Criteria

Ponding sites were identified by finding depressions in the terrain wherein (1) water can pond, (2) the pond is contained within a sewershed boundary and (3) the pond contains a stormsewer inlet. The idea behind these criteria is to identify ponds that form around stormsewer inlets which have reached or exceeded their capacity. These ponds also must be contained within sewershed boundaries because each pond must be associated with a specific sewershed to be entered into the city's hydrological model. Figure 10 demonstrates these criteria which guided the identification of sewershed ponds.

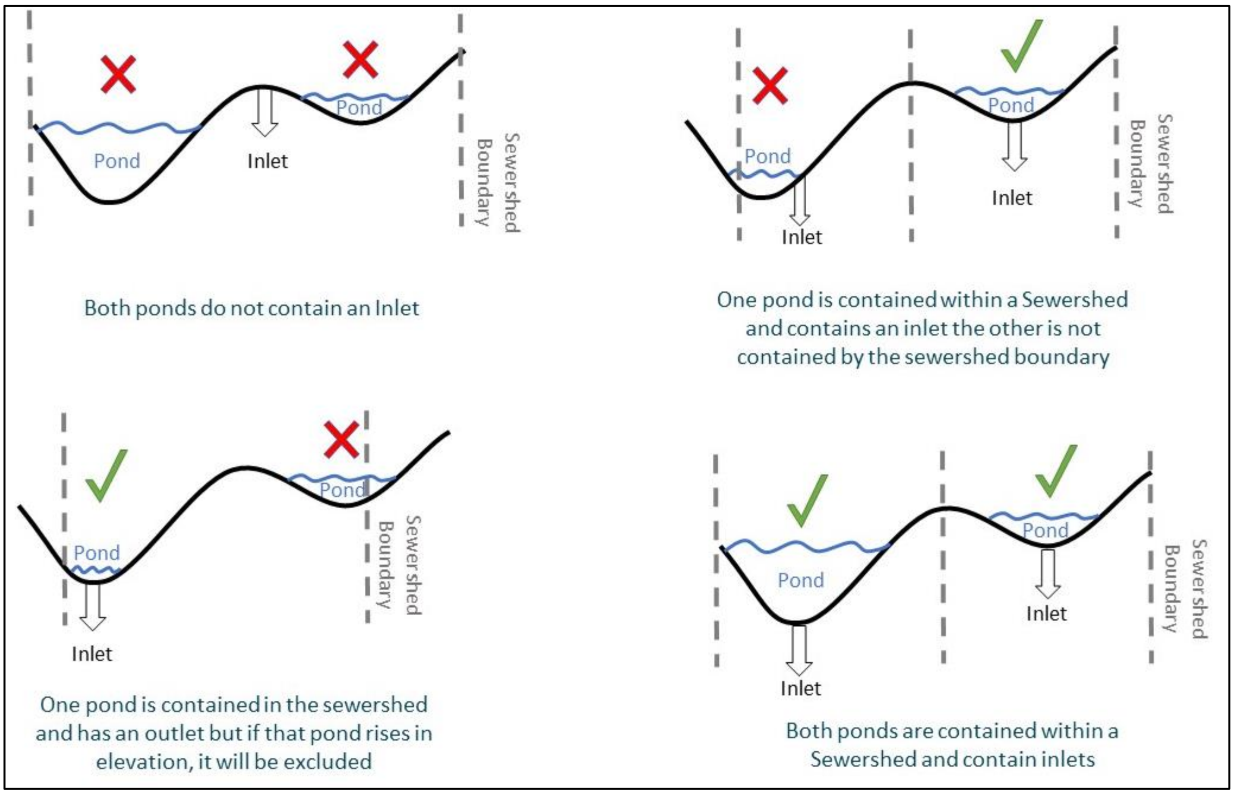


Figure 10: Ponds were excluded in this thesis if they did not contain an inlet, or they extended beyond sewershed boundaries. This figure provides a profile view of scenarios where ponds meet (green check mark) or do not meet (red "X") these criteria.

2.2.3 Obtaining Ponding Potential and Pond Volumes

Identifying each ponds and determining their area and average depth was done using the Model Builder application in ArcGIS. The process was broken into 10 steps which are summarized below. A fill depiction of the process can be found in *Appendix B*.

Steps 1 and 2 involved reading in base datasets, projecting data, adding building shapefile to the DTM and extracting the inlet and sewershed shapefiles from the larger VAV database DTM. The Norwegian Water Resource and Energy Directorate's (NVE) guidelines *How to Find Drainage Lines with GIS* were followed for the preparation of the DTM (NVE, n.d.).

Step 3 identified the lowest point in each sewershed and measured the distance from this point to the sewershed inlet. This step was not necessary for finding the potential ponds but provided valuable insight for the researcher.

Step 4 involved modifying the DTM so each sewershed had terrain that was either positive or negative depending on its relation to the elevation of its associated stormsewer inlet. Terrain that lay above the stormsewer inlet had positive values while terrain that lay below the inlet had negative values. Terrain that was equal to the elevation of the stormsewer inlet had a value of 0 (See ***Error! Reference source not found.***).

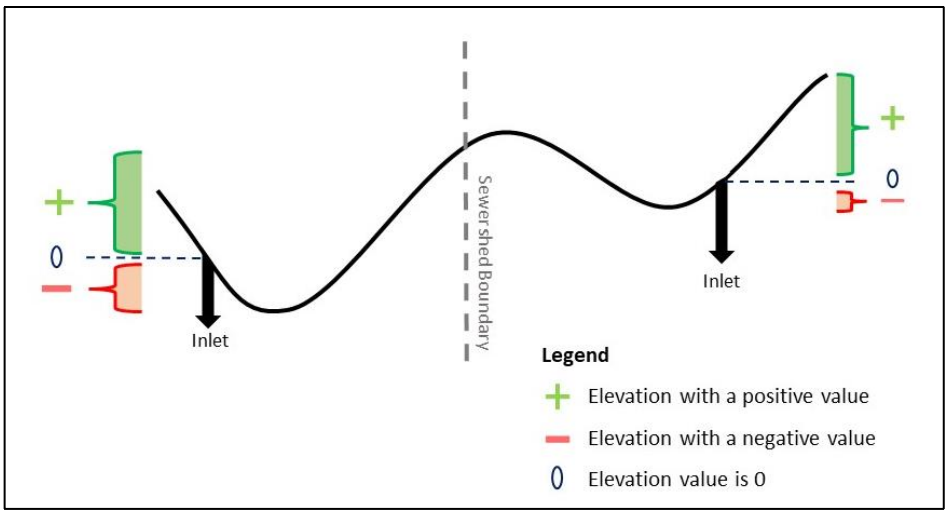


Figure 11: Profile view of sewershed and elevation after the completion of the Step 3 reclassification of the Terrain Analysis.

Steps 5, 6 and 7 simulated overflowing the stormsewer inlets and extracting the resulting ponds that met the criteria of Figure 10. This was done by calculating the areas less than or equal to a specific elevation above the stormsewer inlet (ranging from 1cm to 590cm) then extracting the resulting shapefiles (i.e. ponds) that contained a stormsewer inlet and did not intersect with the sewershed boundary. Figure 12 demonstrates these steps by showing the ponds that met the criteria at certain depths but extended beyond their sewershed at higher depths.

11 different ponds were extracted for areas that sit 0-10cm above each stormsewer inlet (calculated at 1cm intervals), 39 shapefiles were extracted for areas that sit 20-400cm above each stormsewer inlet (calculated at 10cm intervals) and 4 shapefiles were extracted for areas that sit 450-590cm above stormsewer inlets (calculated at 50cm intervals and one 40cm interval between 550cm and 590cm). No ponds could be extracted above 590cm as they either did not exist or spread beyond the boundaries of their sewershed since all buildings had a default height of 600cm. Steps 7 and 8 were the final steps in which the area and average depth of each pond were determined.

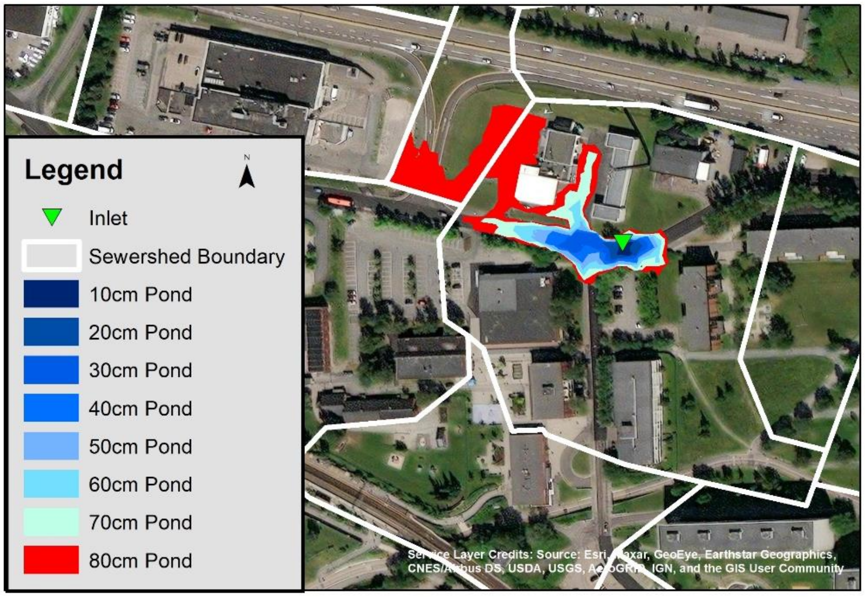


Figure 12: Potential ponds that form at different depths around a sewershed inlet. The pond that forms with a depth of 80 cm (coloured red) is not contained by the sewershed boundary and thus the maximum depth of this potential pond is 70 cm.

This GIS analysis process was guided by the free online support websites Esri Technical Support (Esri, n.d.-b), GIS Stack Exchange (Stack Overflow, n.d.), and ArcGIS Resources (Esri, n.d.-a). The analysis relied heavily on the ArcMap's spatial analysis and geostatistical tools including *Raster Calculator*, *Zonal Statistics* and *Select by Location* to identify and measure the sewershed ponds.

2.2.4 Google Earth Investigation

The final step in the terrain analysis involved examining the 50 largest ponds using Google Earth and Google Street View. As the conditions surrounding the potential ponds could not be viewed in person, a combination of Google Earth satellite imagery and Google Street Views was used to gain some insight on the terrain surrounding the largest identified ponds.

2.3 Hydrological Modelling

The Oslo VAV currently uses the Stormwater Management Model 5.2.0 (SWMM) hydrological modelling software developed by the United States Environmental Protection Agency (EPA).

2.3.1 Model Inputs

The inputs for the Alna SWMM model are structured based on the type of hydraulic or hydrological “object” that is being modelled. The Alna Model is made up of *Subcatchments* (i.e. sewersheds) *Junctions/Nodes* (i.e. inlets and manholes), *Conduits* (i.e. sewers), *Outfalls* and *Rain Gauges*. Each object has attributes which can be filled in by the model user. Some attributes are needed for the model to run (e.g. subcatchments area, or node Invert elevation) while others can be left blank. NIVA provided the VAV Alna Model in a configuration file with the attributes filled in ahead of time using the attributes detailed in Table 4.

2.3.1 Running the Model

The model was run under both dry conditions (i.e. with no precipitation input) and wet conditions (i.e. with a specific precipitation input) to calculated the impacts caused by runoff independently from those caused by sewage. A detailed explanation of this calculation is present below in Section 2.3.2.

The wet conditions consisted of 2-year, 5-year, 20-year, 50-year, 100-year, and 200-year precipitation events with a duration of 20 minutes for all and an additional duration of 30 minutes, 60 minutes and 1440 minutes for the 200-year precipitation event. These conditions are the current precipitation scenarios that the Alna SWMM Model had available and are used to assess the conditions of the hydrological dynamics within the Alna system. The simulated rain inputs were calculated using a hyetograph with data collected by the Hovin rain gauge which is centrally located within the study area. The scenarios simulate rain scenarios in five-minute intervals where the precipitation peaks 1/3rd of the way into the chosen duration.

Table 4: The objects and attributes used in the Alna SWMM Model. The attributes displayed in the table are those attributes that have values in the Alna SWMM Model. Attributes without entered values are excluded (except for Surcharge Depth and Ponded Area).
**Surcharge Depth and Ponded Area were originally left blank but were filled in during this study, using the values obtained from the terrain analysis.*

Model Object	**Attributes used in the Alna SWMM Model**	**Attribute Explanation**
Subcatchments (i.e. Sewersheds)	· X-Coordinate	Horizontal location of centroid
	· Y-Coordinate	Vertical location of centroid
	· Rain Gauge	Rain gauge associated with the subcatchment
	· Outlet	The outlet or subcatchment that receives the runoff from this subcatchment
	· Area	Area (hectares)
	· Width	Width of the overland flow path (meters)
	· % Slope	Average percent slope
	· % Imperv	Percent of land covered by impervious surfaces
	· N-Imperv	Manning's N for overland flow over the impervious part of the subcatchment
	· N-Perv	Manning's N for overland flow over the pervious part of the subcatchment
	· Dstore-Imperv	Depth of depression storage on impervious area
	· Dstor-Perv	Depth of depression storage on pervious area
	· % Zero-Imperv	Percent of the impervious area with no depression storage
	· Subarea Routing	Type of internal routing of runoff between pervious and impervious areas
	· Percent Routed	Percent of runoff routed between subareas
	· Infiltration	Infiltration parameters of subcatchment
Junctions Nodes (i.e. inlets and manholes)	· X-Coordinate	Horizontal location of junction
	· Y-Coordinate	Vertical location of junction
	· Inflow	Presence of external inflow
	· Treatment	Presence of treatment for pollution
	· Invert Elevation	Inver elevation of the junction (meters)
	· Maximum Depth	Maximum depth of the junction (meters)
	· Initial Depth	Depth of water at the junction at the start of the

		simulation
	· Surcharge Depth*	Additional depth of water beyond the maximum depth (i.e. depth of pond formed above junction)
	· Ponded Area*	Area of ponded area above the junction
Conduits Links (i.e. sewers)	· Inlet Node	Name of node on the inlet end of the conduit
	· Outlet Node	Name of node on the outlet end of the conduit
	· Shape	geometric properties of the conduit cross section
	· Maximum Depth	Maximum depth of the conduit's cross section (meters)
	· Length	Conduit length (meters)
	· Roughness	Manning's roughness coefficient
Outfalls Nodes	· X-Coordinate	Horizontal location of the outfall
	· Y-Coordinate	Vertical location of the outfall
	· Inflow	Presence of external inflow
	· Treatment	Presence of treatment for pollution
	· Invert Elevation	Inver elevation of the outfall (meters)
	· Tide Gate	Presence of tide gate to prevent backflow
	· Type	Type of outfall boundary conditions (Free, Normal, Fixed, Tidal, or Time Series)
Rain Gauges	· X-Coordinate	Horizonal location of rain gauge
	· Y-Coordinate	Vertical location of rain gauge
	· Rain Format	Format in which rain data are supplied (Intensity, Volume, or Cumulative)
	· Rain Interval	Recording time interval between gage readings (decimal hours or minutes)
	· Snow Catch Factor	Factor that corrects gauge reading for snowfall
	· Data Source	Source of rainfall data (timeseries or file)
	· Time Series	Name of the time series with rainfall data
	· Rain Units	Depth units for rain (mm)

2.3.2 Adding Ponding Data

Ponding capacity which includes *Ponded Area*, and *Surcharge Depth* are optional inputs for *Junctions* (i.e. Inlets) but the current Alna SWMM Model has left these fields blank. This means that when a stormsewer inlet reaches its capacity to take in stormwater, the model either removes any excess water that the inlet cannot take in, or all excess water is stored above the inlet until such time that the water can be released into the inlet.

Both these options are inaccurate representations of what is likely happening in the sewersheds, wherein some stormwater is ponding around inlets (i.e. stored on site) and some stormwater is running off into neighbouring sewersheds or waterways. Adding the ponding capacity of each stormsewer inlet provides a more accurate representation when inlets reach their capacity to evacuate stormwater.

Once the ponding potential for stormsewer inlets were determined using GIS, this data was entered into the Alna SWMM Model which was run with and without ponding data in 9 different rain scenarios.

2.3.3 Model Outputs

The Alna Model outputs are vast and consist of a *status report* and *summary results*.

The *status report* includes (but is not limited to) results for the system as a whole and the quality of the simulation. By using mass balance equations, the model reports on the *runoff quantity continuity* and *flow routing continuity*. **Error! Reference source not found.** presents an example of summary report results from a 2-year 20-minute simulation. This thesis focuses

```
****************
Analysis Options
****************
Flow Units ............... CMS
Process Models:
  Rainfall/Runoff ........ YES
  RDII ................... NO
  Snowmelt ............... NO
  Groundwater ............ NO
  Flow Routing ........... YES
  Ponding Allowed ........ YES
  Water Quality .......... NO
Infiltration Method ...... HORTON
Flow Routing Method ...... DYNWAVE
Surcharge Method ......... EXTRAN
Starting Date ............ 01/01/2004 00:00:00
Ending Date .............. 01/01/2004 00:20:00
Antecedent Dry Days ...... 0.0
Report Time Step ......... 00:05:00
Wet Time Step ............ 00:05:00
Dry Time Step ............ 01:00:00
Routing Time Step ........ 60.00 sec
Variable Time Step ....... YES
Maximum Trials ........... 8
Number of Threads ........ 10
Head Tolerance ........... 0.001500 m
```

```
**************************        Volume         Volume
Flow Routing Continuity        hectare-m       10^6 ltr
**************************     ---------      ---------
Dry Weather Inflow .......      2937.804      29378.348
Wet Weather Inflow .......        29.791        297.909
Groundwater Inflow .......         0.000          0.000
RDII Inflow ..............         0.000          0.000
External Inflow ..........         0.000          0.000
External Outflow .........         4.712         47.123
Flooding Loss ............      2914.311      29143.413
Evaporation Loss .........         0.000          0.000
Exfiltration Loss ........         0.000          0.000
Initial Stored Volume ....         0.000          0.003
Final Stored Volume ......        41.531        415.315
Continuity Error (%) .....         0.237
```

```
**************************        Volume          Depth
Runoff Quantity Continuity     hectare-m             mm
**************************     ---------        -------
Total Precipitation ......       126.595         11.300
Evaporation Loss .........         0.030          0.003
Infiltration Loss ........         4.619          0.412
Surface Runoff ...........        37.381          3.337
Final Storage ............        83.730          7.474
Continuity Error (%) .....         0.660
```

Figure 13: Status Report Results excerpt. Underlined values were focused on in this study.

primarily on result for *external outflow, flooding loss, and final storage volume* as these were the factors that changed the most when the model was run with and without ponding data.

External outflow represents the amount of water which exited through outfalls. *Flooding loss* represents all the water that left the modelled system and whose end destination was not determined. *Final storage volume* represents any water that is still within the system at the end of the simulation. This is typically water that is still in pipes, in storage tanks, treatment areas, or ponded around inlets

2.3.1 Summary Report

The *summary results* provide tables that list results for each subcatchments (sewershed), junction/node (manhole/inlet/outfalls), and link (pipe) in the system . This study focuses on junction/node results, specifically the number of nodes flooded. Each time the model was run, the ID of each node that experience flooding (i.e. water exceeding the maximum height of the inlet or manhole). The number of flooded nodes was recorded under all 9 rain scenarios with

Figure 14: Status Report Results Excerpt. The underlined outputs were the focus in this study.

and without ponding in effect and the difference was used to measure the impact of ponding. SWMM provides more information on node flooding, such as the amount of time each node flooded, however time restrictions prevented the researcher from obtaining a more detailed analysis in this regard. Finally, the flooded nodes were mapped using GIS to examine the spatial distribution of the flooded nodes.

2.3.2 Isolating Stormwater Impact from Sewage Impacts

The Alna SWMM Model represents a system that is not fully contained and measures both sewage and stormwater. This means some water that originates within its boundaries (as either rain fall or sewage) is sent outside its boundaries via pipes. SWMM considers all the piped water that leaves the boundaries of the Alna Catchment System to be *flooding loss*. Thus, to calculate the model output results related exclusively to stormwater (and not sewage), the following steps were taken.

1. The model was run "dry" (without any rain inputs)
2. The model was run "wet" (with rain inputs) but with *no ponding* in effect

3. The “dry” results were subtracted from the “wet” results to establish the baseline stormwater impacts when ponding is not considered.
4. the model was run “wet” *with ponding* data in effect
5. The “dry” results were subtracted from the “wet” *with ponding* results
6. The difference was measured between the “wet” *with ponding* results and the “wet” *without ponding* results.
7. The remaining difference was then divided by the “wet” *without ponding* results to determine the impact ponding data had in percentage.

Figure 15 shows these steps in a mathematical formula.

Steps 1 - 3: $$R_2 - R_1 = B$$

Steps 4 - 6: $$B - (R_3 - R_1) = D$$

Steps 7: $$\frac{D}{B} = C$$

R_1 – Model results with no rain inputs, without ponding

R_2 – Model results with rain inputs, without ponding

R_3 – Model results with rain inputs, with ponding

B – Baseline Scenario (i.e.impacts of rain on system)

D – Difference (i.e.difference between impacts of rain with and without ponding data)

C – Change (i.e. percent change or impact of ponding data on rain scenarios)

Figure 15: Formulas used to calculate the impact ponding data has during rain scenarios.

3 Results

3.1 Terrain Analysis Results

3.1.1 Pond Dispersal

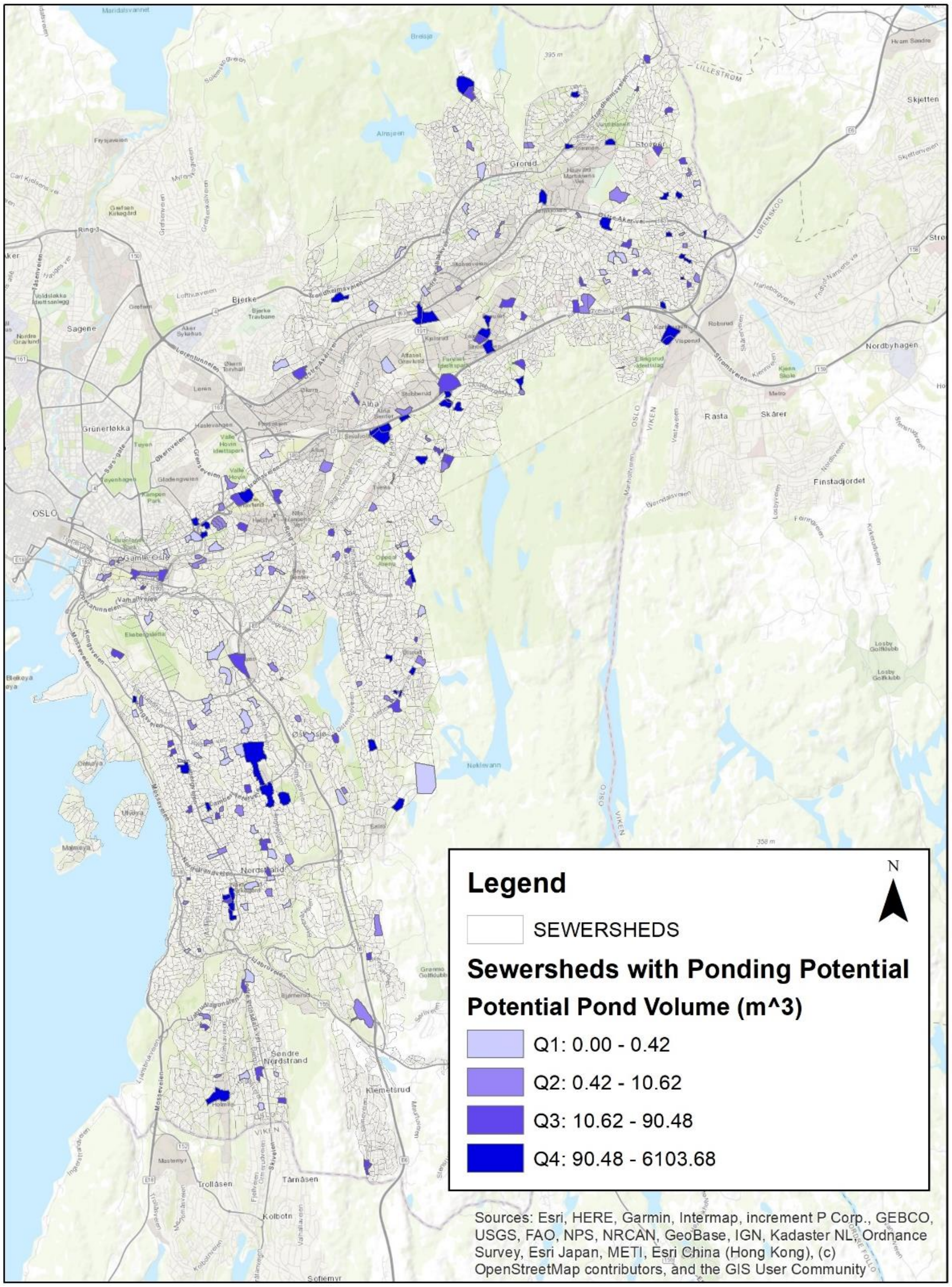


Figure 16: Map of sewersheds with ponding capacity and those that did not have ponding capacity. The capacity of water storage in each sewershed is broken into quartiles representing the maximum volume (m^3) of water each pond could store.

As shown in Figure 16, the GIS terrain analysis found that the majority of sewersheds did not have inlets with ponding potential. A total of 348 sewersheds, approximately 4 percent of all sewersheds were determined to have some inlet ponding potential. This suggests that if stormsewer inlets meet or exceed their capacity to evacuation runoff, or if they experience sewer overflow, most of the excess runoff will not pond around the inlet but will continue to flow downhill to neighbouring sewersheds or pond elsewhere.

The location of potential inlet ponds was widely dispersed across the study area with larger capacity ponds and smaller capacity ponds being located both near the city centre and towards the outer edges of the study area Figure 16.

The low number of potential ponds is likely because most inlets are not located at the lowest point of their associated sewershed. In fact, out only 1 percent of inlets were located within 5 meters from the lowest point in their sewershed. On average sewershed inlets were approximately 50 meters from the lowest point in their sewershed leading to much of the simulated runoff within sewersheds to flow away from or past inlets (*Figure 14*). As mentioned in the Methods section, inlet locations are in part determined by choosing the manholes that causes the least pipe flow error which tends to be manholes that are more centrally located in the sewershed.

Figure 17: Sewershed inlets rarely corresponded to the lowest point in each sewershed. The area below the inlet (in blue) represents runoff that is neither captured by inlets nor potential ponds surrounding inlets.

While the ground cover under each potential pond was not calculated, the sewershed shapefile had data on the percentage of permeable and impermeable land coverage for the entire sewershed area. By observing this data, it was determined that only 8 out of the 348 sewersheds with ponding potential were in sewersheds with over 50 percent impervious surface. While this may suggest that the remaining 340 sewersheds ponds have a potential to cover some permeable areas, further investigation is needed.

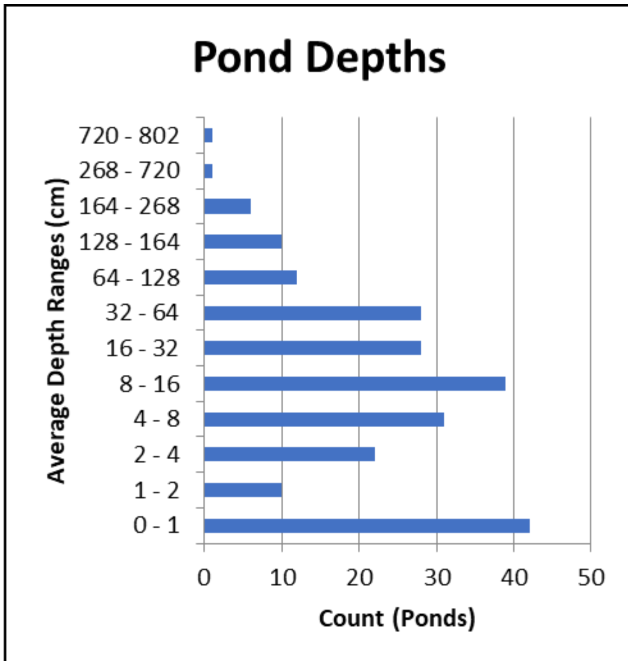
3.1.2 Pond Characteristics

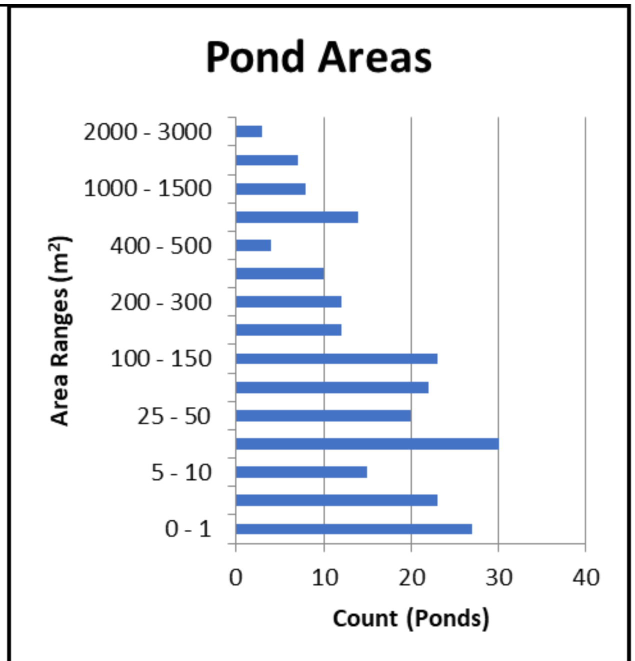
Table 5 provides a statistical summary of the identified ponds and their storage capacities. Ponds raged from both being shallow with a wide coverage to deep with small coverage and in total could store approximately 39,193.20 cubic meters of water.

Table 5: Potential Ponds Summary Statistics

Potential Ponds Count: 230			
	Depth (cm)	Area (m^2)	Volume (m^3)
Min	0.3	0.68	0.002
Max	801.7	2914.06	6103.68
Mean	32.8	246.33	170.41
Median	9.2	50.67	5.94
Standard Deviation	71.29	487.26	559.33
Total	N/A	56655.32	39193.20

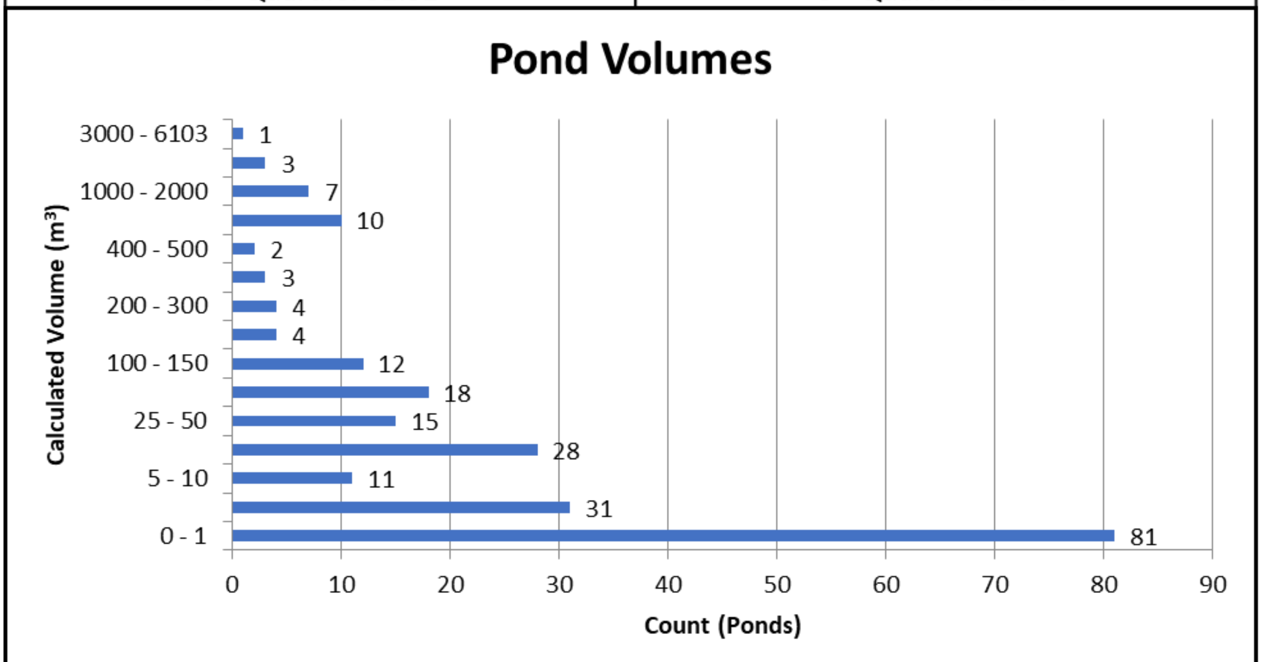
The ponds depths and areas ranged widely as is demonstrated in Figure 18. Most potential ponds were made up of relatively small ponds which could store between 0.58m^3 to 10m^3 of water before the pond overflowed or extended into a neighbouring sewersheds.





Pond Depths: 1st Quartile: 2.40cm | 2nd Quartile: 9.18 | 3rd Quartile: 32.32

Pond Areas: 1st Quartile: 7.89 | 2nd Quartile: 50.67 | 3rd Quartile: 213.79



1st Quartile: 0.25 | 2nd Quartile: 5.97 | 3rd Quartile: 79.46

Figure 18: Depth, area, and volume results of potential ponds

3.1.3 Inlet Connections

Additionally, the type of stormsewer which the inlets were connected to was examined as some inlets connect to a combine stormsewer system (i.e. pipes that carry both stormwater and sewage) and some connected to pipes that strictly carry stormwater. Figure 19 shows the location and the type of system each inlet with potential ponding is connected to. Of the 340 inlets associated with potential ponds, 84 inlets (37%) were connected to combine sewer systems, and the remaining 146 (63%) were connected to storm sewers systems. It appears that the number of combine sewer inlets increases as one approaches the sentrum except for a cluster in the northern section of the study area. Older parts of city often have combined sewer systems and cities switch to separate sewer systems as they expand. This may be an indication of this tendency.

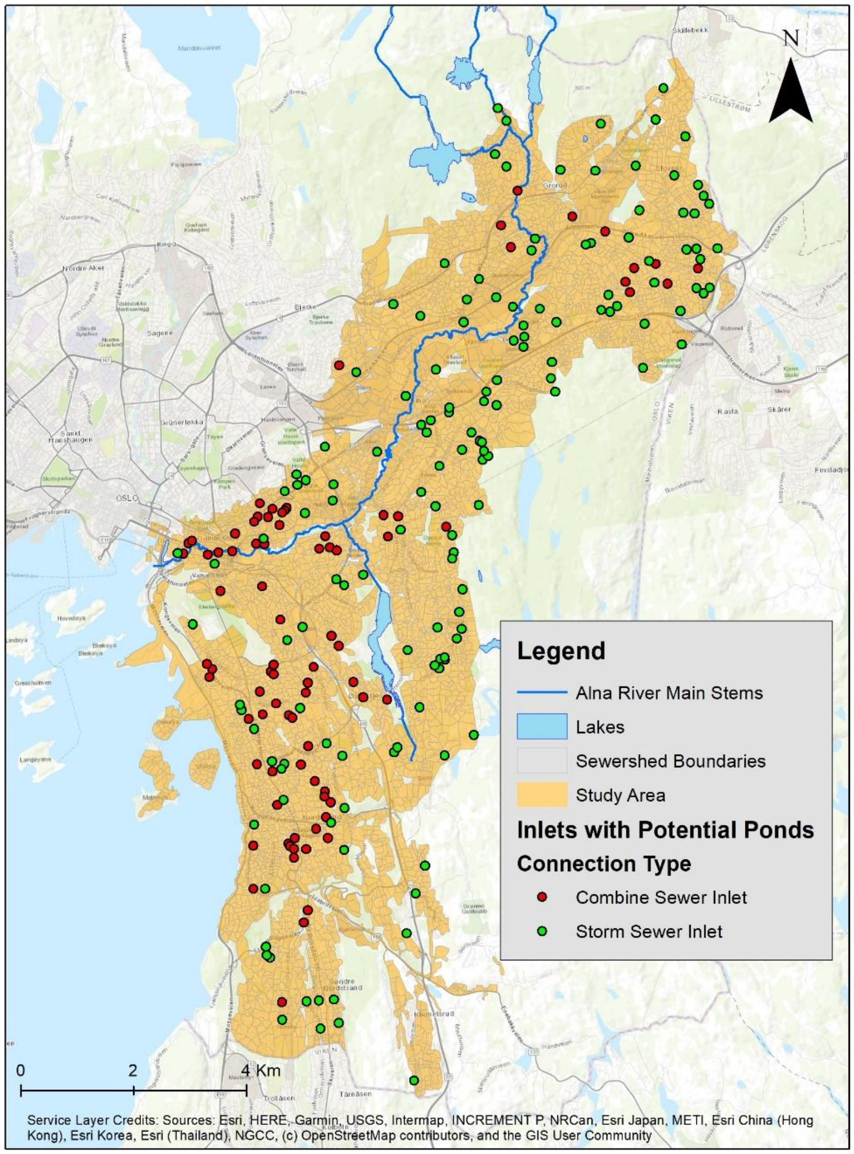


Figure 19: Potential pond inlets types. Combine sewer inlets (red dots) connect to pipes that carry both stormwater and sewage. Storm sewer inlets (green dots) connect to pipes that only carry stormwater.

3.1.4 Google Imagery Investigation

60 of the ponds with the largest volumes were further investigated using Google Earth and Google Street View to understand the surroundings of these ponds. The investigation revealed that the majority of large ponds were situated in parking lots and along railroad tracks, while the remaining ponds were located in roads, gullies, and potentially, construction sites. The prevalence of large ponds in parking lots and railroad tracks is likely due to the fact that these infrastructures are built relatively flat and can cover large amounts of area. Thus, as ponds develop, they have a large amount of area they can cover before they meet a drop in elevation. Large ponds in roads may be due to the same factors (when roads are running flat) and have the added barrier of curbs. As most of the potential pond's depth were around the standard curb height it seems natural that ponds would form along them. On the other hand, gully ponds and potential construction sites, tended to have smaller areas with greater depth. While tree cover made it difficult to verify, it's possible that some of these ponds were in fact stormwater detention or retention ponds, seeing as they had an inlet near their centre. Figure 20 provides some examples of the ponds that were investigated.

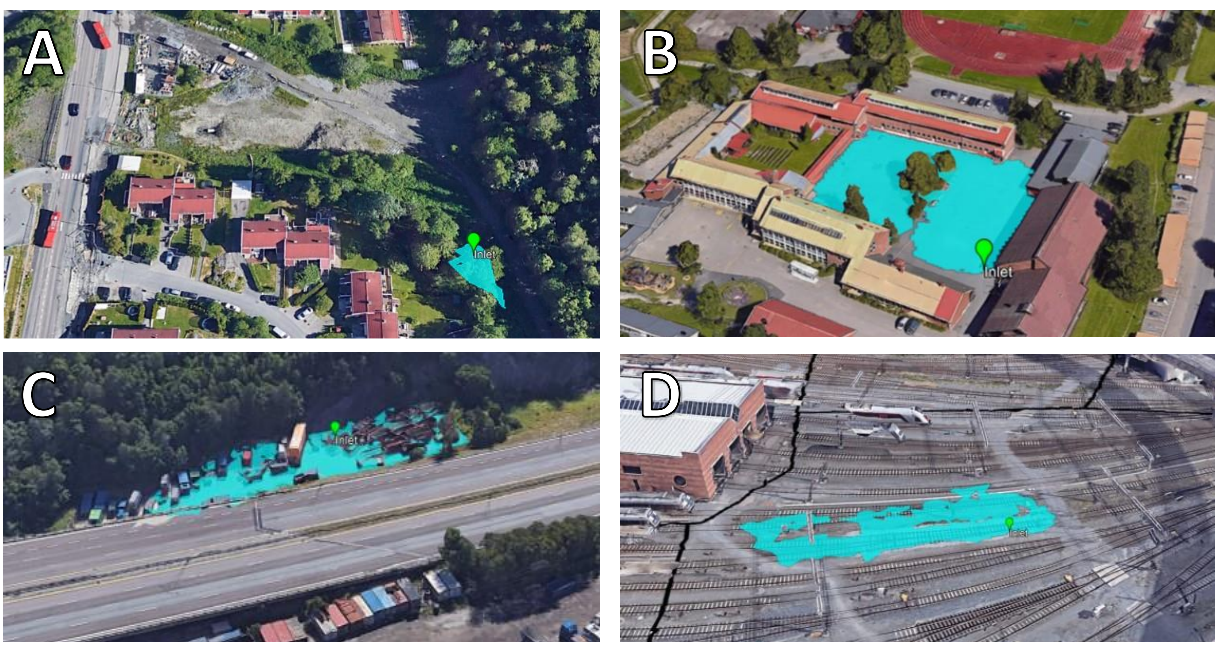


Figure 20: Google Earth Images of potential ponding areas and associated inlets. (A) Potentially a construction site or detention pond. (B) A parking lot boxed in by buildings. (C) A parking area near the highway. (D) Railroad tracks near Oslo Sentrum {Google, n.d. #58}

3.2 Modelling Results

After the potential pond data was entered into the Alna SWMM Model, the model was run under all 9 rain scenario scenarios both with and without ponding to measure the impact and once with no precipitation inputs to establish a baseline as mentioned in Section 2.3.2. Tables 17 through 19 show the calculated change in *external outflow*, *flooding loss* and *final storage volume*, results produced in the summary reports.

3.2.1 Flood Loss

Table 6: Flooding Loss results with and without potential ponding data entered and ran under all 9 precipitation scenarios. Impact of ponding data is calculated by dividing the runoff captured by the flooding loss of the "no ponding" scenario.
** The baseline (dry) scenario has been subtracted out of Flooding Loss thus all Flooding Loss is rain related (not sewage related).*

Precipitation Scenario	Flooding Loss* (Hectare meters)	Runoff Captured by Ponds (Hectare meters)	Percent Change (Hectare meters)
2-year 20-minute no ponding	19.544	19.544	100%
2-year 20-minute ponding	0		
5-year 20-minute no ponding	38.201	22.108	58%
5-year 20-minute ponding	16.093		
20-year 20-minute no ponding	73.312	73.312	100%
20-year 20-minute ponding	0		
50-year 20-minute no ponding	102.49	23.061	23%
50-year 20-minute ponding	79.429		
100-year 20-minute no ponding	129.043	23.489	18%
100-year 20-minute ponding	105.554		
200-year 20-minute no ponding	143.69	8.575	6%
200-year 20-minute ponding	135.115		
200-year 30-minutes no ponding	101.479	23.163	23%
200-year 30-minute ponding	78.316		
200-year 60-minute no ponding	19.257	19.257	100%
200-year 60-minute ponding	0		
200-year 1440-minute no ponding	0.005	0.005	100%
200-year 1440-minute ponding	0		

Table 6 displays results for *Flooding Loss* before and after ponding data was added. The Flooding Loss column displays the amount of water that escaped the stormwater system due to inlets being unable to take in runoff or sewer overflow. The 200-year 20-minute rain scenario resulted in the most runoff escaping the system both when ponding data was absent (143.69 hectare-meters) and when ponding data was added (135.155 hectare-meters. The 100-year 1440-minute rain scenario resulted in the least runoff escaping the system. Only 0.005 hectare-meters of runoff was not captured by the stormwater system when no ponding data was added, and all runoff was captured by the system when ponding data was added.

The Runoff Captured column displays the difference between Flooding Loss before and after ponding data was added which equates to the amount of runoff captured when ponds were added. Ponds captured the most runoff (73.312 hectare-meters) during 20-year 20-minute rain scenario and the least runoff (0.005 hectare-meters) during the 200-year 1440-minute event. While this demonstrates the range of runoff volume captured by ponds, it does not indicate under which scenarios ponds have the greatest impact.

The final column, Percent Change, does just that by displaying the percentage of runoff captured when ponding is added. During the 2-year 20-minute, 20-year 20-minute, 200-year 60-minute, and 200-year 1440-minute rain scenarios, ponds were able to capture 100 percent of the runoff which, in the absence of ponds, would have escaped the storm sewer system. The added pond data had the least impact in the 200-year 20-minute rain scenario, only capturing 6% of the runoff that was escaping the system when no ponding data was entered. This suggests that in a high intensity short duration rain scenario, ponding has a low effect, most likely because the ponds do not have enough time to drain the vast amounts of runoff they are receiving into their inlets and thus the ponds overflow, sending the runoff elsewhere. This assumption is supported by the fact that when the 200-year rain scenario is stretched out to 30 minutes rather than 20, ponds can capture more runoff by volume and have a higher impact.

In summary, the *Flooding Loss* results reveal that inlet ponds are likely capturing large volumes of water, that would otherwise runoff or pond elsewhere. The results also suggest that adding ponding substantially increases the accuracy of Alna SWMM Model by reducing the amount of runoff that is not accounted for, especially in lower return period rain scenarios and/or long duration rain scenarios.

3.2.2 External Outflow

An important caveat to make for External Outflow results is that the majority of water that enters the stormwater system is piped outside of the model's boundaries. *External Outflow* only measures water that exits outflows within the model's boundaries thus these results only represent a fraction of the water that is conveyed by pipes. This results in the relatively low External Outflow volumes which are displayed in Table 7.

Table 7: External Outflow results. Additional Outflow Contributed by Ponds is calculated by dividing the Additional Outflow by the External Outflow of the "no ponding" scenario.
** The baseline (dry) scenario has been subtracted out of External Outflow thus all outflow is rain related (not sewage related).*

Precipitation Scenario	External Outflow (Hectare meters)	Additional Outflow Contributed by Ponds (Hectare meters)	Percent Change
2-year 20-minute no ponding	15.937	0.007	100.04%
2-year 20-minute ponding	15.944		
5-year 20 minute no ponding	3.888	0.824	121.19%
5-year 20-minute ponding	4.712		
20-year 20 minute no ponding	6.97	0.006	100.09%
20-year 20-minute ponding	6.976		
50-year 20 minute no ponding	3.888	0.01	100.26%
50-year 20-minute ponding	3.898		
100-year 20 minute no ponding	12.806	0.003	100.02%
100-year 20-minute ponding	12.809		
200-year 20 minute no ponding	14.393	0.005	100.03%
200-year 20-minute ponding	14.398		
200-year 30 minute no ponding	11.418	0.005	100.04%
200-year 30-minute ponding	11.423		
200-year 60 minute no ponding	2.959	0.009	100.30%
200-year 60-minute ponding	2.968		
200-year 1440 minute no ponding	0.001	0.012	1200.00%
200-year 1440-minute ponding	0.013		

Figure 21 displays a graph of the External Outflowl volumes with and without ponding in the different rain scenarios. It’s clear that External Outflow increased when ponding data is added, thus some of the excess runoff captured by ponds is likely making to the measured outlets. It also seems that the volume of outflow decreases as rain scenarios increase in duration.

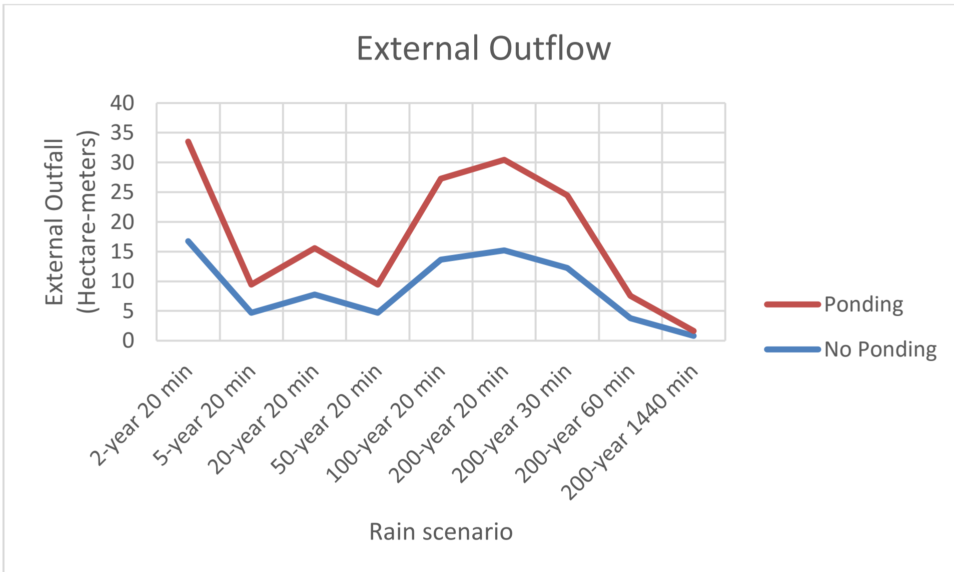


Figure 21: External Outfall results in the 9 rain scenarios. Results for both no ponding and ponding scenarios are sporadic as rain intensity increases and declines as rain duration increases. However ponding scenarios consistently result in more External Outflow.

However, as these results only account for a small portion of water captured by the storm sewer system, to understand these results properly, a more in-depth examination of the layout of the stormwater system is needed.

3.2.3 Final Storage

Final Storage is the last *status report* result analysed in this study and it shows the amount of stormwater that remains in the storm sewer system at the end of each model simulation.

In all rain scenarios, the addition of ponding data substantially increases the Final Storage volume. Final Storage in the “no ponding” scenarios had a relatively wide range from 0.004 hectare-meters to 9.373 hectare-meters, whereas the “ponding” scenario’s Storage Contribution were relatively stable, ranging from 21.63 hectare-meters to 23.986.

The combination of these two dynamics resulted in a large and impactful change when they were compared.

Table 8: Final Storage Results

Precipitation Scenario	Final Storage (Hectare meters)	Additional Storage Contributed by Ponds (Hectare meters)	Percent Change (Hectare meters)
2-year 20-minute no ponding	9.373	23.986	255%
2-year 20-minute ponding	33.359		
5-year 20-minute no ponding	5.376	21.85	406%
5-year 20-minute ponding	27.226		
20-year 20-minute no ponding	6.995	22.098	315%
20-year 20-minute ponding	29.093		
50-year 20-minute no ponding	5.376	21.85	406%
50-year 20-minute ponding	27.226		
100-year 20-minute no ponding	8.668	23.056	265%
100-year 20-minute ponding	31.724		
200-year 20-minute no ponding	9.051	23.482	259%
200-year 20-minute ponding	32.533		
200-year 30-minute no ponding	8.897	23.157	260%
200-year 30-minute ponding	32.054		
200-year 60-minute no ponding	5.708	21.878	383%
200-year 60-minute ponding	27.586		
200-year 1440-minute no ponding	0.004	21.630	540750%
200-year 1440-minute ponding	21.634		

Adding ponding data increased Final Storage by a minimum of 255% and a maximum of 540,750% implying that lots of the water captured by ponds (between 21 and 24 hectare-meters) is still in the stormwater system at the end of each modelled scenario. It is important to note that SWMM includes water located in ponds in its Final Storage, so some of this stored water may be in inlet ponds at the end of the model scenario.

A final observation regarding the *Status Report* results is that the 5-year 20-minute flood scenario tended to be an outlier scenario in regard to Flood Loss, External Outfall, and Final Storage's precent change results (see Tables 6, 7 and 8) . The reason behind this anomaly could not be determine and further research is needed to assess if this is a modelling error or if something about the stormwater system itself causes the 5-year scenario to act differently.

3.2.4 Node Flooding

While this study does not assess the impact of inlet ponds on a node-by-node basis, the *summary results* of *node flooding* were extracted, summarized and mapped to help gain an understanding of how and where node flooding occurs, and the impact ponding has on this. Node flooding occurs when inlets exceed their capacity to take in stormwater and when manholes or inlets overflow (i.e. sewer overflow).

As is show in Table 9, and Figure 22, in every rain scenario, more nodes flooded when ponding data was added to the model. The 200-year 20-minute rain scenario resulted in the most nodes flooding (7933 nodes) as well as the greatest increase in flooded nodes when ponding data was added (97 additional nodes). This matches up with the previous Flooding Loss result indicated that under high-intensity, short duration rain scenarios, the impact the inlet ponds have on capturing runoff is at its lowest.

The increase in flooded nodes is likely due to the increase in stormwater entering the system as the ponds direct more runoff into inlets. The number of new nodes flooded, after adding ponds, was relatively consistent (staying between 87 and 97 nodes) whereas the Total Flooding Volume had more variable results. Of the 9 rain scenarios, only the 100-year 20-minute rain event resulted in an increase in Total Flooding Volume while the rest reported a decrease.

*Table 9: Node Flooding Results. Difference is calculated by subtracting the "no ponding" scenario from the "ponding scenario. *Nodes Flooded and Total Flooding Volume results are shown after baseline values have been subtracted.*

2yr 20min			
	No Ponding	Ponding	Difference
Nodes Flooded	2284	2381	97
Total Flooding Volume (m^3)	195489	195384	-105
5yr 20min			
	No Ponding	Ponding	Difference
Nodes Flooded	4521	4608	87
Total Flooding Volume (m^3)	382131	382083	-48
20yr 20min			
	No Ponding	Ponding	Difference
Nodes Flooded	6443	6532	89
Total Flooding Volume (m^3)	733422	733377	-45
50yr 20min			
	No Ponding	Ponding	Difference
Nodes Flooded	7087	7183	96
Total Flooding Volume (m^3)	1025345	1025336	-9
100yr 20min			
	No Ponding	Ponding	Difference
Nodes Flooded	7483	7579	96
Total Flooding Volume (m^3)	1290956	1290986	30
200yr 20min			
	No Ponding	Ponding	Difference
Nodes Flooded	7836	7933	97
Total Flooding Volume (m^3)	1591843	1591833	-10
200yr 30min			
	No Ponding	Ponding	Difference
Nodes Flooded	7193	7286	93
Total Flooding Volume (m^3)	1015423	1015393	-30
200yr 60min			
	No Ponding	Ponding	Difference
Nodes Flooded	3192	3283	91
Total Flooding Volume (m^3)	192690	192.58	-110
200yr 1440 min			
	No Ponding	Ponding	Difference
Nodes Flooded	2	94	92
Total Flooding Volume (m^3)	54	0	-206

Average Difference for Node Flooding Results (Across All Rain Scenarios)	
Minimum Difference in Flooded Node Count	87
Maximum Difference in Flooding Node Count	97
Average Difference in Flooded Node Count	93
Minimum Difference in Flooding Volume	-206
Maximum Difference in Flooding Volume	30
Average Difference in Total Flooding Volume	-59.22

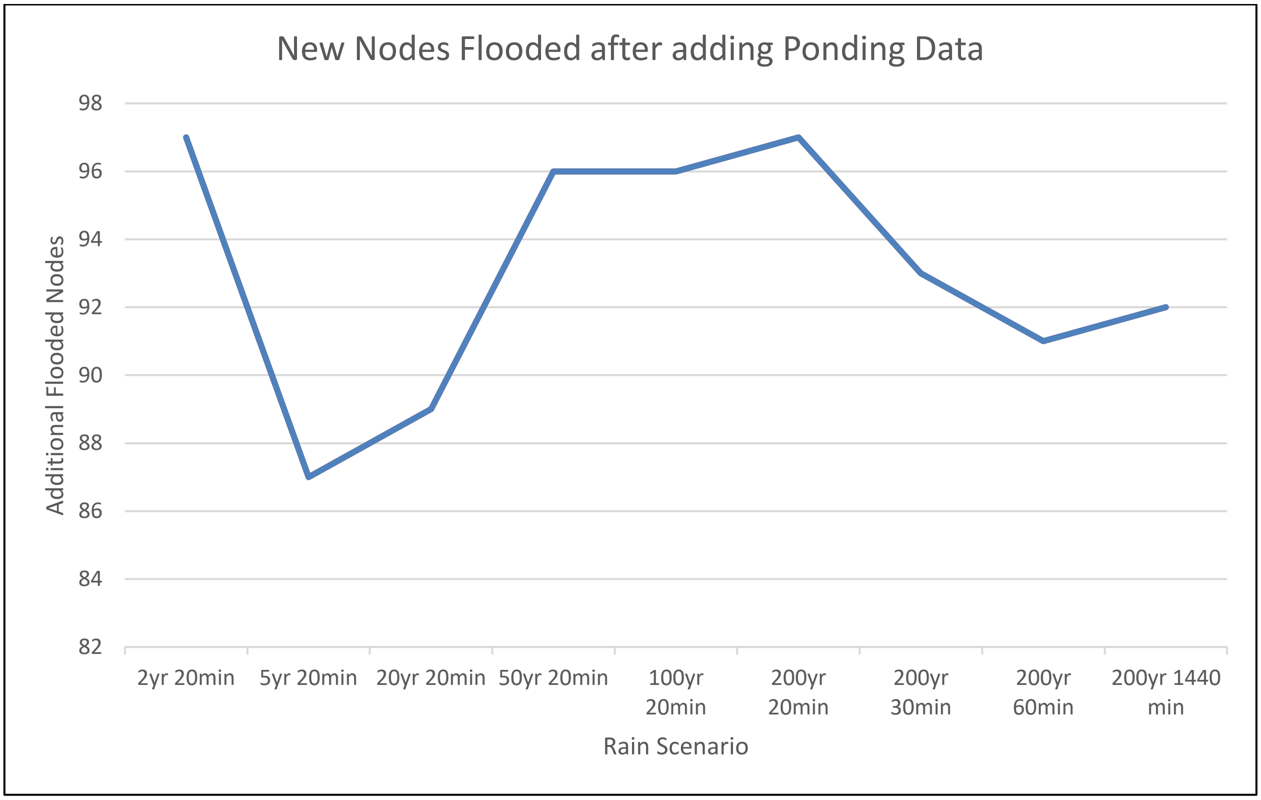


Figure 22: Impact of Ponding Data on Node Flooding. The plotted values in this graph are taken from the "Difference" column in Table 9.

Figure 22 visualizes the impact ponding data had on node flooding. Generally speaking and node flooding seems to increase as the intensity of the rain scenario grows and decrease as the duration of the scenario increases but there are exceptions to both these trends, mainly the 2-year 20-minute rain scenario (which continues to be an outlier) the 100-year 20-minute scenario (which showed no change compared to the 50-year scenario) and the 200-year 1440-minute scenario (which increase the number of flooded nodes compared to the 200-year 60-minute event). This suggests that the impact of ponding data on node flooding is influenced by other factors in addition to rain intensity and duration. These factors could include the layout of the stormwater system itself and the location of the inlet ponds within the system. Future analysis on the layout and proximity of the flooded nodes should be done to gain more insight on the influencing factor..

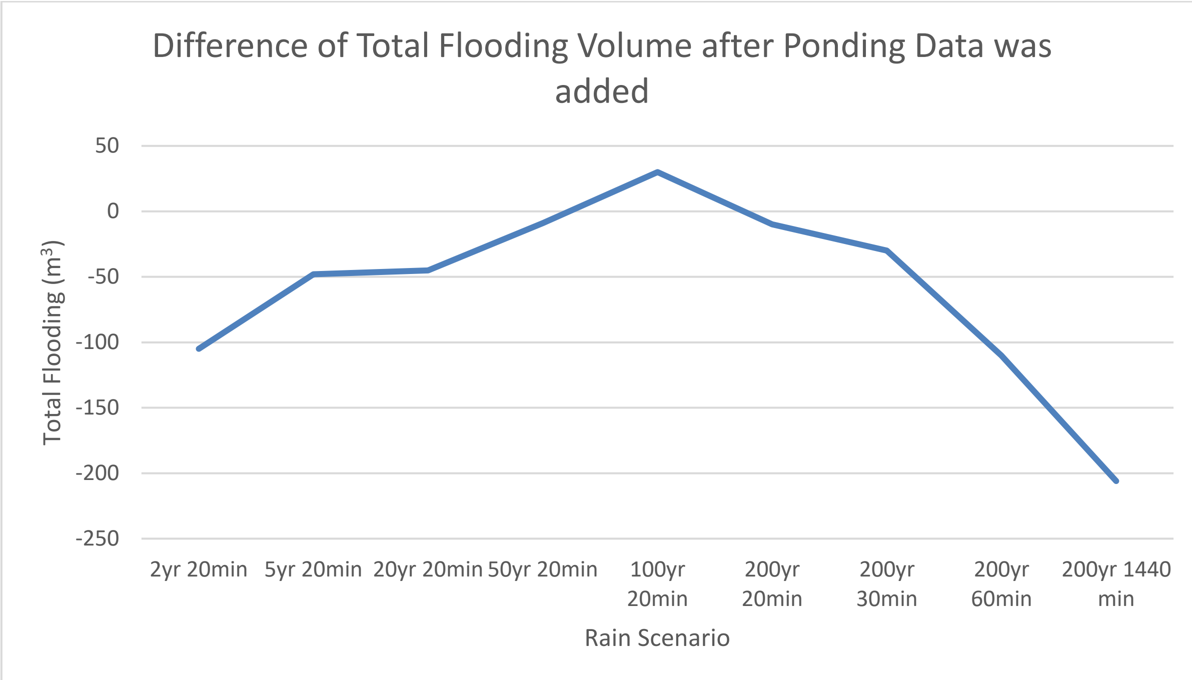


Figure 23: Impact of adding ponding data on Total Flooding Volume. The plotted values in this graph are taken from the "Difference" column in Table 9.

Figure 22 plots the impact of ponding data on Total Flooding Volume across all flooded nodes. These results presenting a seemingly clearer relation between ponding impact, rain scenario intensity, and rain scenario duration. For all but one scenario the addition of ponding resulted in less Total Flooding Volume. Figure 23 shows that ponding reduces Total Flood Volume the most during the lower intensity and longer duration rain scenarios. This suggests that ponds are able prevent the most flooding during these scenarios and in fact contribute to an increase in Total Flooding Volume during the 100-year 20-minute rain scenario.

When both Figure 22 and Figure 23 are considered together, they reveal that the added ponding potential has the two following impacts on node flooding. (1) More nodes experience flooding to some degree but (2) in most cases Total Flooding Volumes are decrease. This could imply that the added runoff that is captured by ponds is widely dispersed within the stormsewer system, leading to a more nodes experiencing flooding but to a much lesser extent on a systems scale. Further research on a more detailed spatial scale is needed to verify this assumption.

4 Discussion

This section will discuss the results of the previous section and delve further into the meaning behind the results as they relate to the aims, objectives, and research questions of this study.

4.1 Potential Impacts of Identified Inlet Ponds

The terrain analysis revealed the ponding capacity for the study area to be widely distributed and variable in storage capacity. The wide distribution of ponds could provide both positive and negative impacts on the hydrological system as whole.

4.1.1 Decentralized Stormwater Detention and LIDs

On the positive side, ponding can reduce the speed of runoff and its ability to accumulate in other areas {Hu, 201{Pour, 2020 #49}7 #50}. These ponds could potentially meet the needs of step-2 in Oslo's water management strategy in that they can "retain or detain" water during medium rain scenarios (City of Oslo, 2016). Additionally, ponding can reduce runoff's ability to erode sediment, pick up pollutants, and contribute to larger scale flooding downstream. A wide dispersal of ponding areas and elevations reduces the overall runoff on a catchment scale whereas lots of potential ponds in a limited area cannot provide these benefits as widely.

Many cities are currently looking to manage stormwater by implementing lots of small-scale flood mitigation infrastructure as opposed to the large grey-infrastructure based solutions of the past (Hellmers et al., 2017). These small-scale, decentralized solutions, sometimes referred to as Low-Impact Development (LID) have gained a lot of attention in the recent decades due to their ability to reduce flooding and improve water quality. Additionally, small-scale, decentralized mitigation measure are more adaptable, cheaper, can be implemented faster, and do not require as much space which is especially beneficial for densely populated areas(Hu et al., 2017; Pour et al., 2020). While much of the discourse around LIDs and decentralized flood mitigation measures focuses on Nature-Based Solutions, which incorporate or mimic nature (i.e. green roofs, permeable pavements, and rain gardens), the inlet ponds identified in this study could provide some of the same benefits or could serve as starting points to implement LIDs such as permeable pavement.

4.1.2 Widespread Flooding and Pollution

Conversely, ponding is essentially small-scale flooding. As these ponds will form because of inlets being overloaded, a wide dispersal of these ponds could indicate a negative challenge for the Alna Catchment System. If these ponds form in sensitive areas, for example near vulnerable infrastructure, heavy traffic areas, near vulnerable residents, or in contaminated areas, they could cause disruption, or harm to neighbouring infrastructure, residents, and the environment. Thus, in these scenarios a wide dispersal of potential ponds could mean a wide dispersal of problem areas which could be harder to address.

The analysis determined that only 16 percent (57 ponds) of the potential ponds touched buildings which implies that most the ponds are not likely to directly impact buildings. Additionally, most of the potential ponds are relatively shallow, with a median depth of 9.2 cm. In Norway, average curb heights range from 4 cm to 10 cm. Thus, many of these ponds, if they surround street inlets, have the potential to be contained by street curbs and have a lower risk of flooding buildings and homes and are more likely to flood streets. In fact, many of the largest ponds, observed via Google Earth sat atop railroad tracks, parking lots, and streets. This implies that there may be transportation related challenges that come into play when these ponds form. It is important to keep in mind that this study only focused on ponds that form around stormsewer inlets thus ponding/flooding may occur elsewhere and cause damage.

Regarding potential environmental or health related impacts, the analysis found that 37 percent of the inlets with ponding potential were connected to combine sewer. This means that when those potential ponds form, it’s possible that the sewer overflow contains sewage mixed in with the stormwater rather than just stormwater. Flooding with sewage can cause health problems both for individuals and the environment (Gibson et al., 1998). Thus, these ponds may have more negative impacts than positive.

4.2 Modelled Impacts of Ponding

4.2.1 Collection of Stormwater

The reduction in flood loss resulting from the ponding data demonstrates the large impact a relatively small number of ponds can have on the hydrology of an urban hydrological system.

Whereas the total ponding potential of all potential ponds was 391,93.20 cubic meters, the largest modelled amount of runoff these ponds were able to divert reached 733,120 during the 200-year 20-minute simulation. The addition of ponding data also demonstrated a substantial impact regarding capturing runoff that was previously unaccounted for, in that the ponds captured 100 percent of Flooding Loss for 4 out of the 9 different rain scenarios.

These finding support the idea that decentralized small-scale stormwater interventions can a substantial impact on reducing surface runoff. In the case of the Alna SWMM Model, lower intensity 20-minute rain events and high intensity rain scenarios with longer durations (i.e. 60 and 1440 minute). That being said it is important to note that the modelled ponds have a very minimal impact (i.e. 6 percent) on Flood Loss during the 200-year 20-minute rain scenario.

Given that the modelled result indicate that the ponds were very effective at detaining stormwater and most effective during moderate rain scenarios, it should be considered in Olso's Stormwater Management Plan under Step 2 of their 3-step stormwater management strategy.

4.2.2 Adding Stormwater to the Stormwater System

While detaining and evacuating rainwater can prevent some of the negative impacts of excess urban runoff, the overall benefits depend on where all that collected stormwater ends up. The analysis of node flooding implies that some of the water capture by inlet ponds resulted in an increase in the number of nodes experiencing flooding. While the total volume of flooding in most (8 out of 9) rain scenarios was decreased when ponds were taken into account, the increase of nodes experiencing flooding is a potential area of concern.

The impact of flooding depends highly on where it occurs. One of the negative effects of conveying stormwater through pipes is that water can collect in these pipes very quickly and cause sewer overflows downstream. This is especially concerning for this study area as there are a higher concentration of combine sewer systems downstream thus when nodes overflow in this area, there is a higher chance that the overflow may contain sewage. In order to verify these risks and better understand the impacts of the added volume of water collected by inlet ponds, further research should be done on a finer scale assessing the nodes that experience flooding.

4.1 Limitations

The limitations of this study focus on the base data, the elements of the Alna SWMM Model, and the limitations of modelling. Urban areas have highly complex terrains that contain small but impactful elements like short curbs, fences, and ramps that could drastically alter surface flow when missed.

The inaccuracies caused by such elements was reduced in this study by using a digital terrain model with a 1-meter resolution. Thus, many of these small impactful urban elements may have been disregarded and it would be advisable in future studies to start with terrain data with a finer resolution (e.g. lidar point cloud data). Additionally, the location and function of the sewershed inlets were not 100% accurate as the inlets have not been ground verified to determine if they were inlets or manholes. This may have resulted in potential "inlet" ponds to actually be ponding which occurs around covered manholes or many potential inlet ponds may have been missed as they were labelled as covered manholes in the base data. This inaccuracy could be remedied in the future if inlets are verified using on the ground verification methods or satellite imagery. As the study area is very large, both these methods will take a substantial amount of time. Given the time restrictions and fact that the City of Oslo uses this inlet data for its model, the researcher chose to proceed with the terrain analysis using the data provided.

Finally, it is worth noting that models in themselves are, by nature, inaccurate representations of a real-world system. The aim of this study was to improve upon an existing hydrological model, even though the final model cannot perfectly depict or predict the impacts of rain on the Alna Catchment System.

5 Conclusion

To conclude, this study demonstrates that the approach of a GIS-based terrain analysis to add to a hydrological model can help provide a more accurate picture of the hydrology within an urban catchment. The terrain analysis provided insight on the distribution and dimensions of potential inlet ponds discovering them to be widely distributed throughout the study area and variable in size. The study was able to improve model accuracy and account for between 6-100 percent of runoff which previously had no determined path or destination, depending on the simulated rain scenario. The study answered the research questions determining the ponding potential around each sewershed inlet and the impact of the potential ponds on the Alna SWMM Model. Specifically, this study assessed the system-wide impacts of the potential ponds discovering that they were very effective at collecting stormwater runoff which had previously alluded the modelled inlets, and the collection of this additional stormwater resulted in, amongst other things, an increase in the number of nodes that experienced flood.

While the study does not assess the potential impact these ponds have on a more local scale (i.e. the area surround the ponds or the flooded nodes), it provides a good starting point by providing the location and extent of each pond as well as system-wide impacts. Additionally, this study does not investigate the impact the ponds have on water quality or sewershed peak flow given that this data is still missing from the model. However, if and when these elements are incorporated into the model, ponding data would be an important part in calculating the impacts.

To quote George Box, a famous British statistician, “all models are wrong, but some models can be useful”(Box, 1976). At their best, models can be used to help inform people on the relationships and patterns within systems so that they can make more educated and effective decisions to influence that system. The addition and analysis of ponding data to the Alna SWMM Model provided insightful information that helps explain the relationship between inlet ponds and the Alna Hydrological System that should be considered for further research. Decision makers at the City of Oslo can use this research to help inform their decisions as they implement their Stormwater Management Plan.

As the risks of urban flooding quickly increase due to climate change, urbanization, and inadequate infrastructure, there is an urgent need to for decision makers to take informed and effective action to mitigate and adapt to the growing impacts. Research of the potential impacts of ponding can help in this regard. As cities improve on their ability to understand, explain, and predict their urban hydrology, they become more equipped to take meaningful and impactful action and help create a more liveable, safe, and healthy city.

References

A. S. Gragne, T. M. M., K. Alfredsen, S. Sægrov, . (2015). *The Kværnerbyen flood of 2nd September 2015: Reconstruction of the Alna River flows and capacity assessment of the culvert-tunnel system* (B1-2015-3). https://www.researchgate.net/publication/303522925_The_Kvaernerbyen_flood_of_2nd_September_2015_Reconstruction_of_the_Alna_River_flows_and_capacity_assessment_of_the_culvert-tunnel_system

Abedin, S. J. H., & Stephen, H. (2019). GIS Framework for Spatiotemporal Mapping of Urban Flooding. *Geosciences*, *9*(2), 77. https://www.mdpi.com/2076-3263/9/2/77

Ahiablame, L. M., Engel, B. A., & Chaubey, I. (2013). Effectiveness of low impact development practices in two urbanized watersheds: Retrofitting with rain barrel/cistern and porous pavement. *Journal of Environmental Management*, *119*, 151-161. https://doi.org/https://doi.org/10.1016/j.jenvman.2013.01.019

AON. (2021). *2021 Weather, Climate and Catastrophe Insite*. A. plc. https://www.aon.com/weather-climate-catastrophe/index.aspx?utm_source=virtual-event&utm_medium=link&utm_campaign=ri_esg-climate-change_all_rin_global_all&utm_content=gated-content&utm_term=2020-report

Benestad, R. E., Lussana, C., Lutz, J., Dobler, A., Landgren, O., Haugen, J. E., Mezghani, A., Casati, B., & Parding, K. M. (2022). Global hydro-climatological indicators and changes in the global hydrological cycle and rainfall patterns. *PLOS Climate*, *1*(5), e0000029. https://doi.org/10.1371/journal.pclm.0000029

Box, G. E. P. (1976). Science and Statistics. *Journal of the American Statistical Association*, *71*(356), 791-799. https://doi.org/10.1080/01621459.1976.10480949

Chen, J., Hill, A. A., & Urbano, L. D. (2009). A GIS-based model for urban flood inundation. *Journal of Hydrology*, *373*(1), 184-192. https://doi.org/https://doi.org/10.1016/j.jhydrol.2009.04.021

City of Oslo. (2016). *Action Plan for Stormwater Management in the City of Oslo - Executive Summary*. [online] Retrieved from https://www.oslo.kommune.no/getfile.php/13166800-1478167579/Content/Politics%20and%20administration/Green%20Oslo/Plans%20and%20programmes/Action%20Plan%20for%20Storm%20Water%20Management%20in%20Oslo%20Excutive%20Summary.pdf

Dittmer, U., Bachmann-Machnik, A., & Launay, M. A. (2020). Impact of Combined Sewer Systems on the Quality of Urban Streams: Frequency and Duration of Elevated Micropollutant Concentrations. *Water*, *12*(3), 850. https://www.mdpi.com/2073-4441/12/3/850

EEA. (2017). *Climate Change, Impacts and Vulnerability in Europe 2016 – An Indicator-based Report*. https://www.eea.europa.eu/publications/climate-change-impacts-and-vulnerability-2016

EPA. (n.d.). *Stormwater Management Model (SWMM)*. United States Government, Environmental Protection Agency (EPA). Retrieved 11/26/2021 from https://www.epa.gov/water-research/storm-water-management-model-swmm

Esri. (n.d.-a). *ArcGIS Resource Center*. https://resources.arcgis.com/en/help/

Esri. (n.d.-b). *Esri Technical Support*. https://support.esri.com/en

Field C.B., V. B., T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley. (2012). *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*. https://www.ipcc.ch/report/managing-the-risks-of-extreme-events-and-disasters-to-advance-climate-change-adaptation/

Gale, E. L., & Saunders, M. A. (2013). The 2011 Thailand flood: climate causes and return periods. *Weather*, *68*(9), 233-237. https://doi.org/https://doi.org/10.1002/wea.2133

George M. Hornberger, J. P. R., Patricia Wilberg, Paolo D'Odorico. (2014). *Elements of Physical Hydrology*. John Hopikins University Press.

Gibson, C. J., Stadterman, K. L., States, S., & Sykora, J. (1998). Combined sewer overflows: A source of Cryptosporidium and Giardia? *Water Science and Technology*, *38*(12), 67-72. https://doi.org/10.1016/s0273-1223(98)00802-6

Gragne, A., Muthanna, T., Alfredsen, K., & Sægrov, S. (2015). *The Kværnerbyen flood of 2nd September 2015: Reconstruction of the Alna River flows and capacity assessment of the culvert-tunnel system*.

Güneralp, B., Güneralp, İ., & Liu, Y. (2015). Changing global patterns of urban exposure to flood and drought hazards. *Global Environmental Change*, *31*, 217-225. https://doi.org/https://doi.org/10.1016/j.gloenvcha.2015.01.002

Hellmers, S., Manojlovic, N., Palmaricciotti, G., & Fröhle, P. (2017). Modelling decentralised systems for urban drainage and flood mitigation. *Journal of Applied Water Engineering and Research*, *5*(1), 61-69. https://doi.org/10.1080/23249676.2015.1128368

Hoegh-Guldberg, O., Jacob, D., Taylor, M., Bindi, M., Brown, S., Camilloni, I., Diedhiou, A., Djalante, R., Ebi, K.L., Engelbrecht, F., Guiot, J., Hijioka, Y., Mehrotra, S., Payne, A., Seneviratne, S.I., Thomas, A., Warren, R., Zhou G. (2018). *Impacts of 1.5ºC Global Warming on Natural and Human Systems* (An IPCC Special Report on the impacts of global warming of 1.5ºC above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty, Issue. I. P. o. C. Change. https://www.ipcc.ch/site/assets/uploads/sites/2/2019/02/SR15_Chapter3_Low_Res.pdf

Holt, E., Koivusalo, H., Korkealaakso, J., Sillanpää, N., & Wendling, L. (2018). *Filtration Systems for Stormwater Quantity and Quality Management - Guideline for Finnish Implementation*.

Hu, M., Sayama, T., Zhang, X., Tanaka, K., Takara, K., & Yang, H. (2017). Evaluation of low impact development approach for mitigating flood inundation at a watershed scale in China. *Journal of Environmental Management*, *193*, 430-438. https://doi.org/https://doi.org/10.1016/j.jenvman.2017.02.020

IPCC. (2022). *Climate Change 2022: Impacts, Adaptation, and Vulnerability*. https://www.ipcc.ch/report/sixth-assessment-report-working-group-ii/

Lewis A Rossman, M. S. (2022). *Stormwater Management Model User's Manuel Version 5.2*. (EPA-600/R-22/030). [online]: Office of Research and Development Retrieved from https://cfpub.epa.gov/si/si_public_record_Report.cfm?dirEntryId=354181&Lab=CESER

Lindholm, O. (2014). *Håndtere overvannet i rør eller på overflaten?* Norsk vannforenings

50-årsjubileum, https://vannforeningen.no/dokumentarkiv/handtere-overvannet-i-ror-eller-pa-overflaten/

Mallin, M. A., Cahoon, L. B., Toothman, B. R., Parsons, D. C., McIver, M. R., Ortwine, M. L., & Harrington, R. N. (2007). Impacts of a raw sewage spill on water and sediment quality in an urbanized estuary. *Marine Pollution Bulletin*, *54*(1), 81-88. https://doi.org/https://doi.org/10.1016/j.marpolbul.2006.09.003

Megen, S. v. (2018). *Urban Stormwater Management in Oslo, Norway* Wageningen University]. Netherlands. https://newwaterways421475860.files.wordpress.com/2018/11/final-version-thesis-urban-stormwater-management-oslo-sjoerd-van-megen_2018_bachelor_thesis.pdf

Niazi, M., Nietch, C., Maghrebi, M., Jackson, N., Bennett, B. R., Tryby, M., & Massoudieh, A. (2017). Stormwater Management Model: Performance Review and Gap Analysis. *Journal of sustainable water in the built environment*, *3*(2), 10.1061/jswbay.0000817. https://doi.org/10.1061/jswbay.0000817

Nirupama, N., & Simonovic, S. P. (2007). Increase of flood risk due to urbanisation: A canadian example. *Natural Hazards*, *40*(1), 25-41. https://doi.org/10.1007/s11069-006-0003-0

NIVA. (2020). *Alna Kunnskapssammenstilling og mulighetsstudie*. https://www.miljodirektoratet.no/globalassets/publikasjoner/m1781/m1781.pdf

NVE. (n.d.). *How to Find Drainage Lines with GIS*. Norges vassdrags og energidirektorat. https://nve.maps.arcgis.com/apps/MapSeries/index.html?appid=fc707330a0e044c8ac38b1727beeeef0&fbclid=IwAR1bfvTaMqxs_TJz-zSZf-X_oNx-MrDX75-AdULkd7ocU-OBygBWGNeph80

O'Donnell, E. C., & Thorne, C. R. (2020). Drivers of future urban flood risk. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *378*(2168), 20190216. https://doi.org/doi:10.1098/rsta.2019.0216

Paule-Mercado, M. A., Lee, B. Y., Memon, S. A., Umer, S. R., Salim, I., & Lee, C. H. (2017). Influence of land development on stormwater runoff from a mixed land use and land cover catchment. *Science of The Total Environment*, *599-600*, 2142-2155. https://doi.org/https://doi.org/10.1016/j.scitotenv.2017.05.081

Pour, S. H., Wahab, A. K. A., Shahid, S., Asaduzzaman, M., & Dewan, A. (2020). Low impact development techniques to mitigate the impacts of climate-change-induced urban floods: Current trends, issues and challenges. *Sustainable Cities and Society*, *62*, 102373. https://doi.org/https://doi.org/10.1016/j.scs.2020.102373

Rosbjerg, D., & Rodda, J. (2019). IAHS: a brief history of hydrology. *Hist. Geo Space. Sci.*, *10*(1), 109-118. https://doi.org/10.5194/hgss-10-109-2019

Salvadore, E., Bronders, J., & Batelaan, O. (2015). Hydrological modelling of urbanized catchments: A review and future directions. *Journal of Hydrology*, *529*, 62-81. https://doi.org/https://doi.org/10.1016/j.jhydrol.2015.06.028

SSB. (2022). *Folkemengden etter kjønn og alder* Statistik sentralbyrå. https://statistikkbanken.oslo.kommune.no/webview/velocity?headers=r&stubs=Bydel&measure=common&virtualslice=Antall_value&layers=Kjnn&layers=Alder&layers=virtual&Aldersubset=1000&study=http%3A%2F%2F10.134.180.90%3A80%2Fobj%2FfStudy%2FBe01-Befolkningen-etter-bydel-kjonn-og-alder-SSB&Alderslice=1000&mode=cube&virtualsubset=Antall_value&v=2&rsubset=1990+-+2022&measuretype=4&cube=http%3A%2F%2Fstatistikkbanken.oslo.kommune.no%3A80%2Fobj%2FfCube%2FBe01-Befolkningen-etter-bydel-kjonn-og-alder-SSB_C1&Kjnnsubset=3&Kjnnslice=3&Bydelsubset=30100%2C30101+-+30118#tag_30100

Stack Overflow. (n.d.). *GIS Stack Exchange*. https://gis.stackexchange.com/

UN. (2019). *World Urbanization Prospects: The 2018 Revision* (ST/ESA/SER.A/420). U. Nations. https://population.un.org/wup/publications/

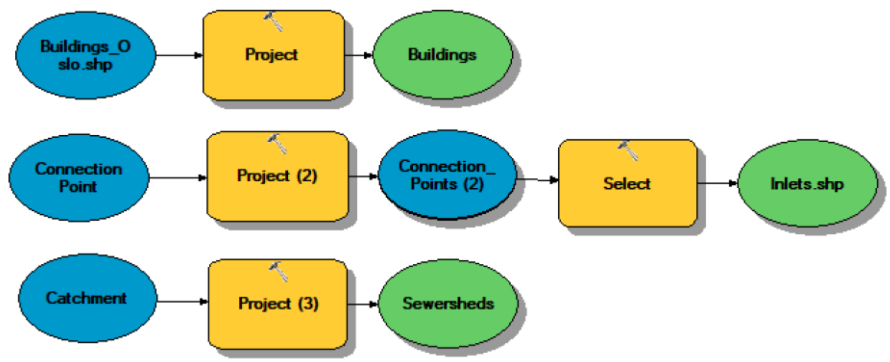
World Bank Group. (2022). *Climate Change Knowledge Portal*. https://climateknowledgeportal.worldbank.org/download-data

APPENDIX A: SUMMARY OF CRITERIA FOR THE DELINEATION OF SEWERSHEDS

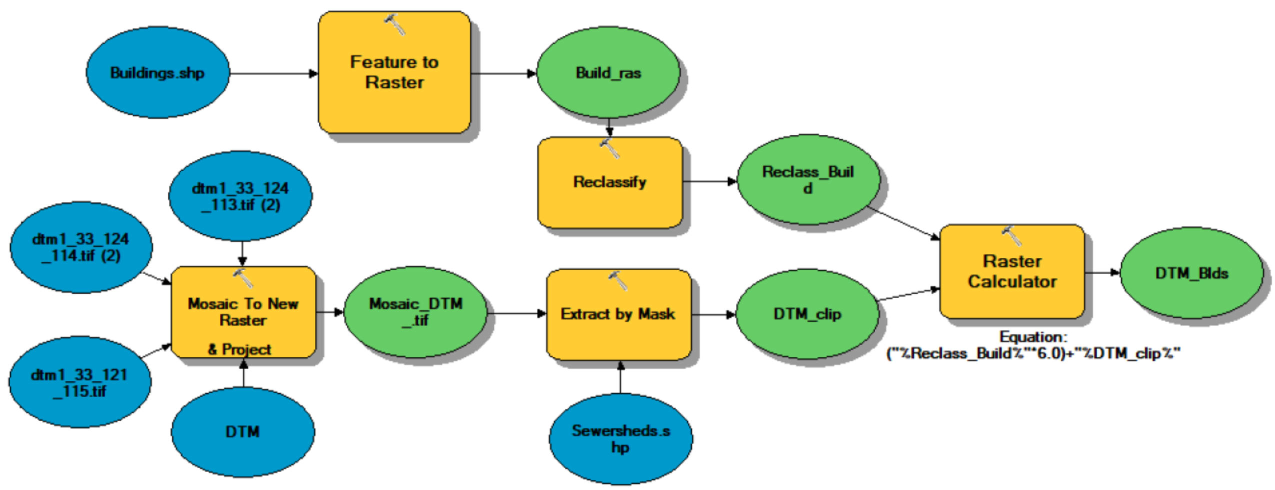
Summarized Criteria for the delineation of Sewersheds
1. Each Sewershed must have an area of maximum 1km^2. 2. The number of waterways that cross the boundary of each sewershed must be as small as possible. 3. Sewersheds should be either on the upper or lower side of floodways when water flows parallel to the desired sewershed boundary to keep the entire floodway in one of the sewersheds. 4. Sewershed boundaries must go around building infrastructure and not cut through them. 5. Sewershed boundaries must run on one side of the road, not in the middle. 6. Sewershed boundaries towards watercourses should follow the FKB watercourse delimitation. 7. Drainage zones or subcatchments should be assessed and ideally each sewershed will have a controlled number of in and out waterways both above and below the surface. 8. Naming of the sewershed is performed separately for each main watercourse

APPENDIX B: 10-STEP METHOD OF TERRAIN ANALYSIS TO FIND POTENTIAL PONDS

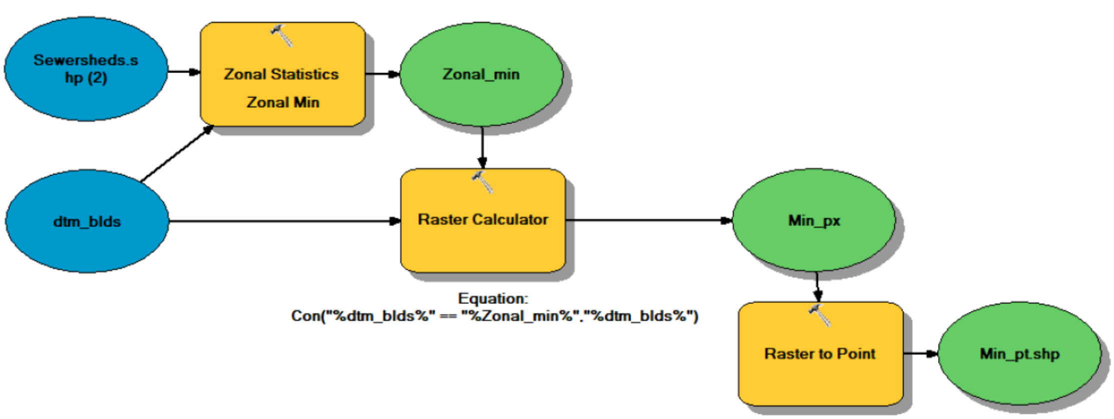
Step 1) Prepare VAV Basedata (Project to UTM zone 32 and extract only stormsewer inlets)



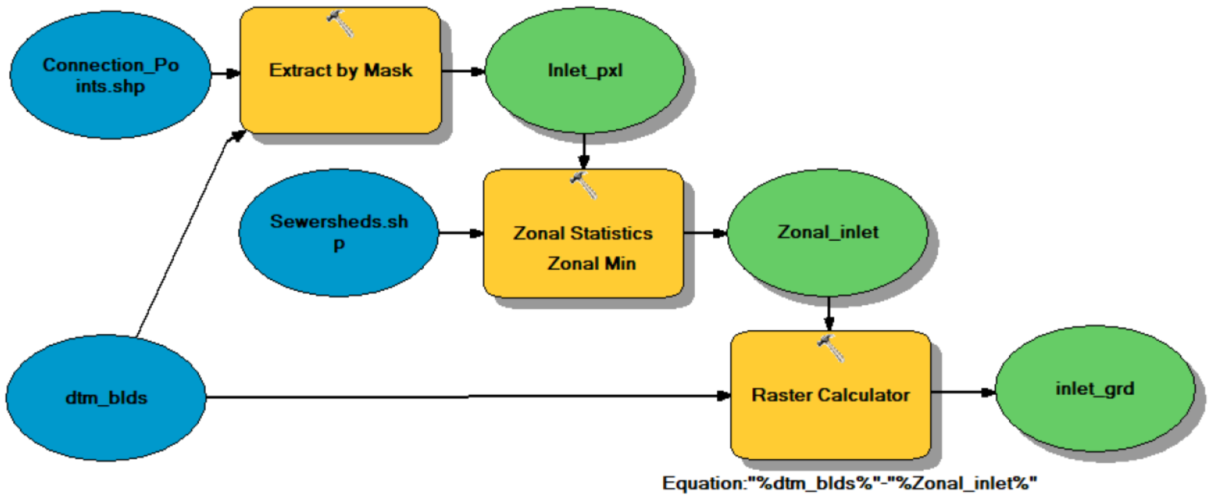
Step 2) Prepare Høydata Digital Terrain Models (mosaic, project, set building height at 6 meters and add buildings to DTM)



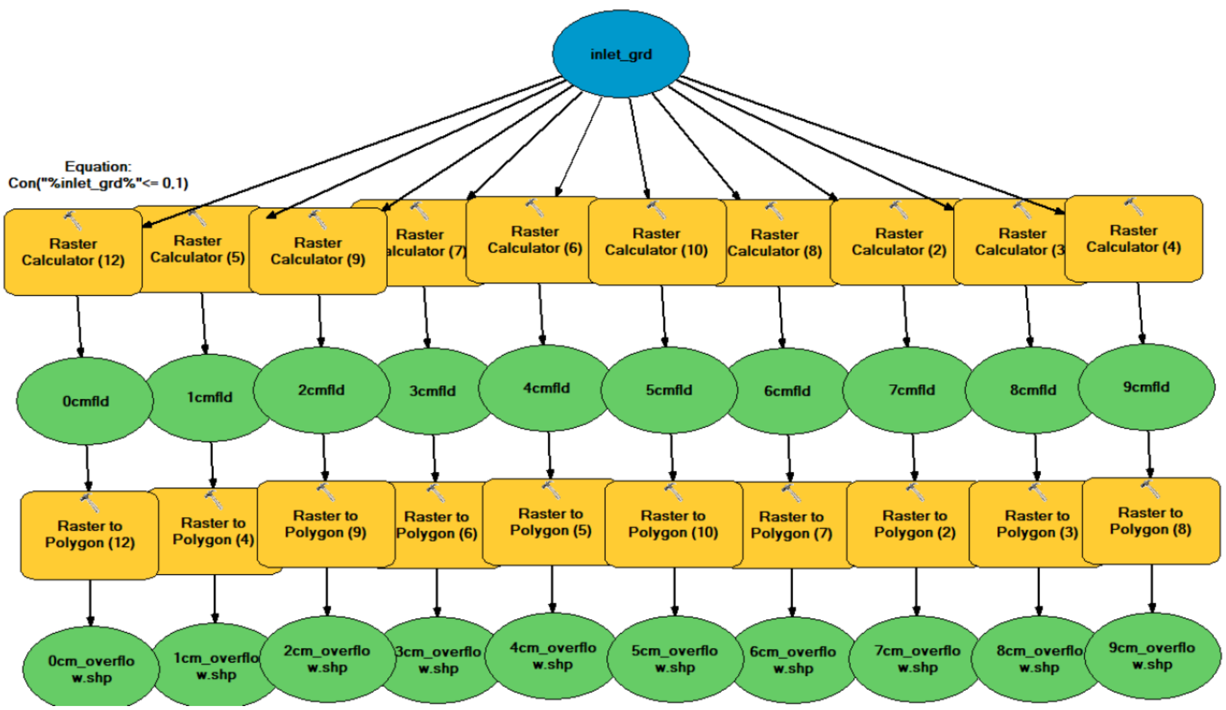
Step 3) Find Lowest Point in Sewershed



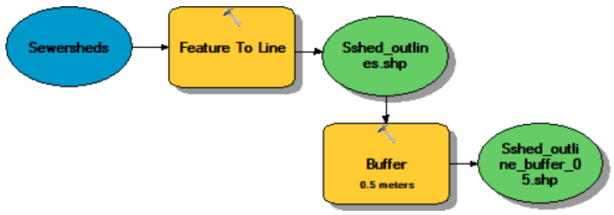
Step 4) Alter DTM so Inlet elevation is “0” in each sewershed



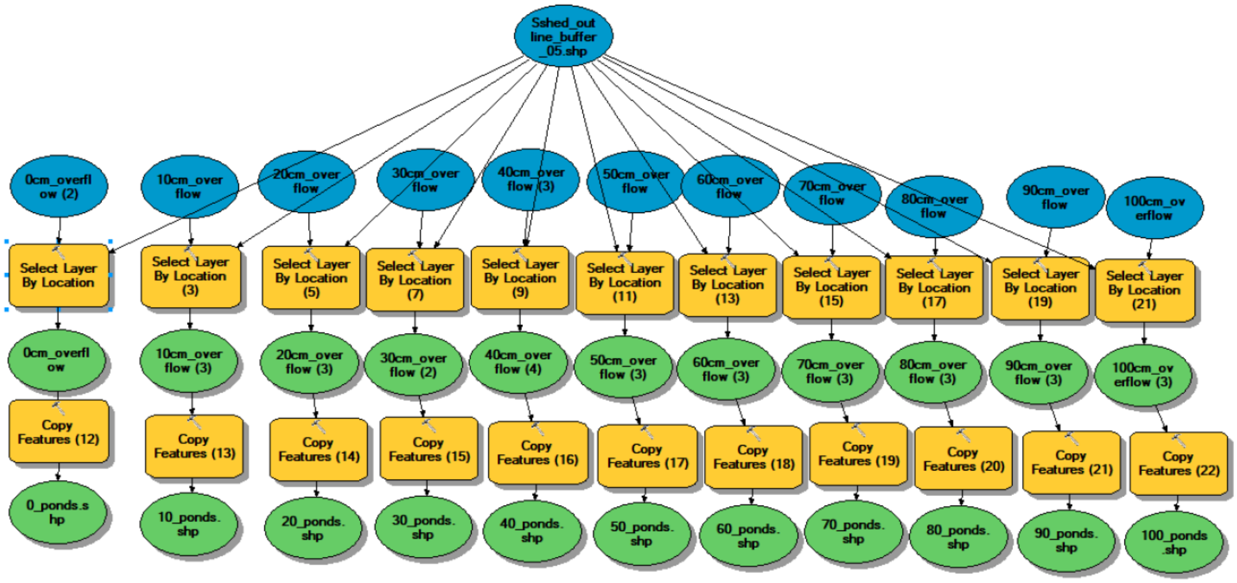
Step 5) Calculate area above inlet in: 1cm steps (0-10 cm), 10 cm steps (10-400 cm), 50 cm steps (400-550 cm +590)



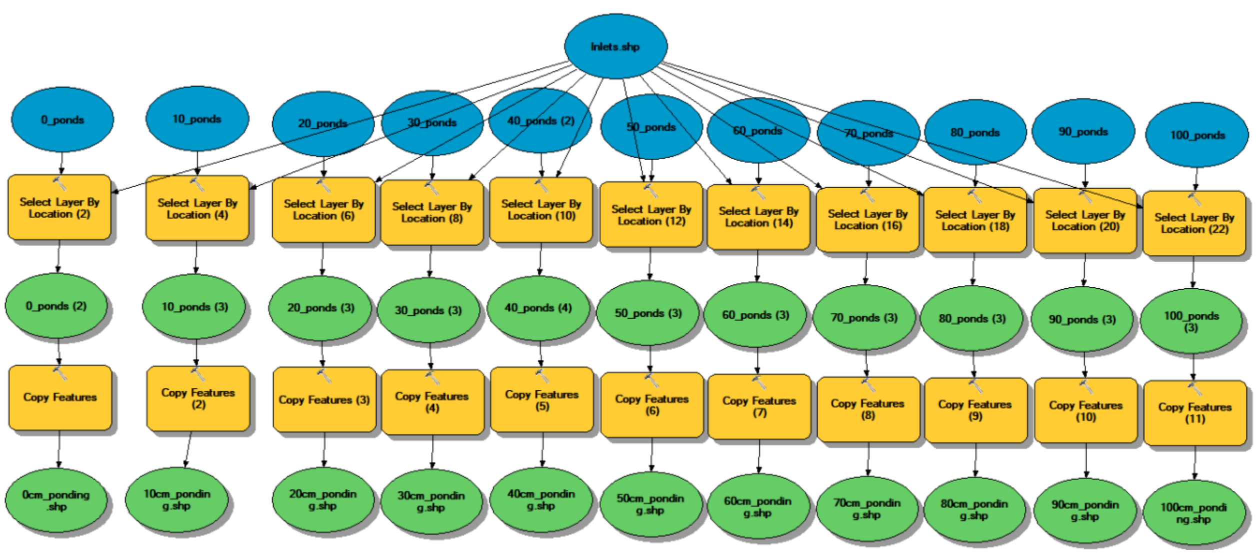
Step 6) Buffer sewershed boundary by 0.5 meters



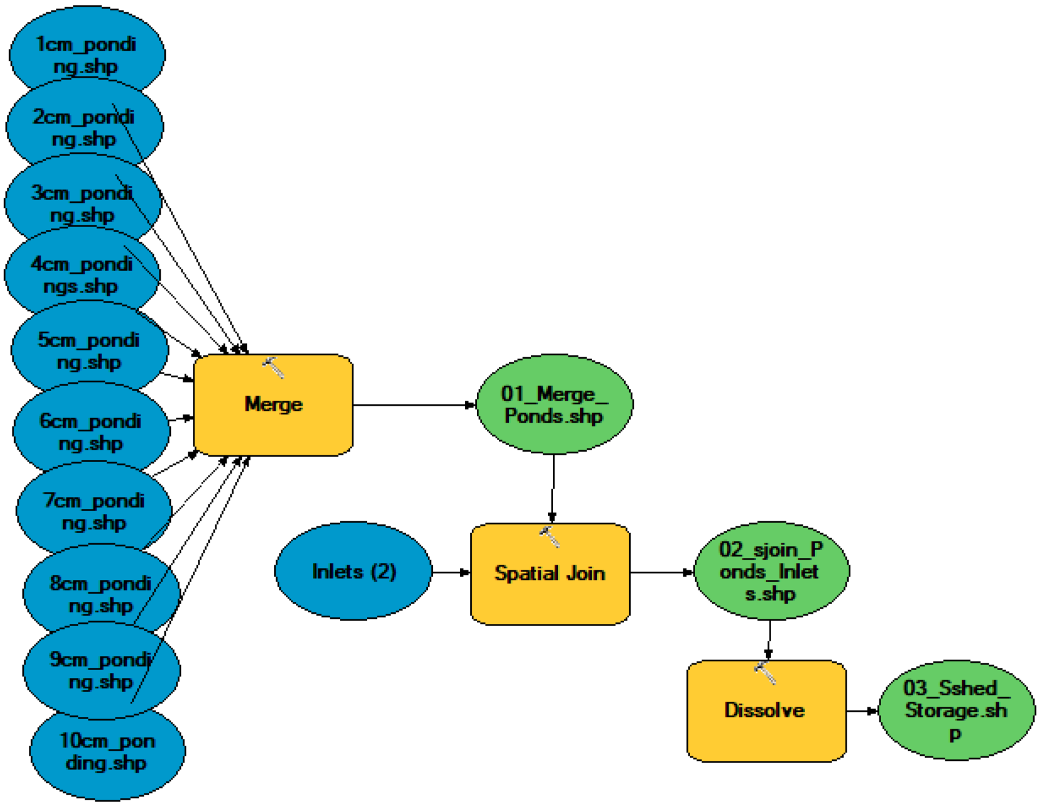
Step 7) Remove ponds that intersect sewershed boundary extract ponds that intersect inlets (process repeated for all overflow values from 0 to 590)



Step 8) Extract ponds that intersect inlets (process repeated for all pond values from 0 to 590)



Step 9) Merge remaining ponds, join with Inlet values and dissolve so only largest ponds remain



Step 10) Alter DTM so pond minimum elevation is 0 then calculate average depth of ponds