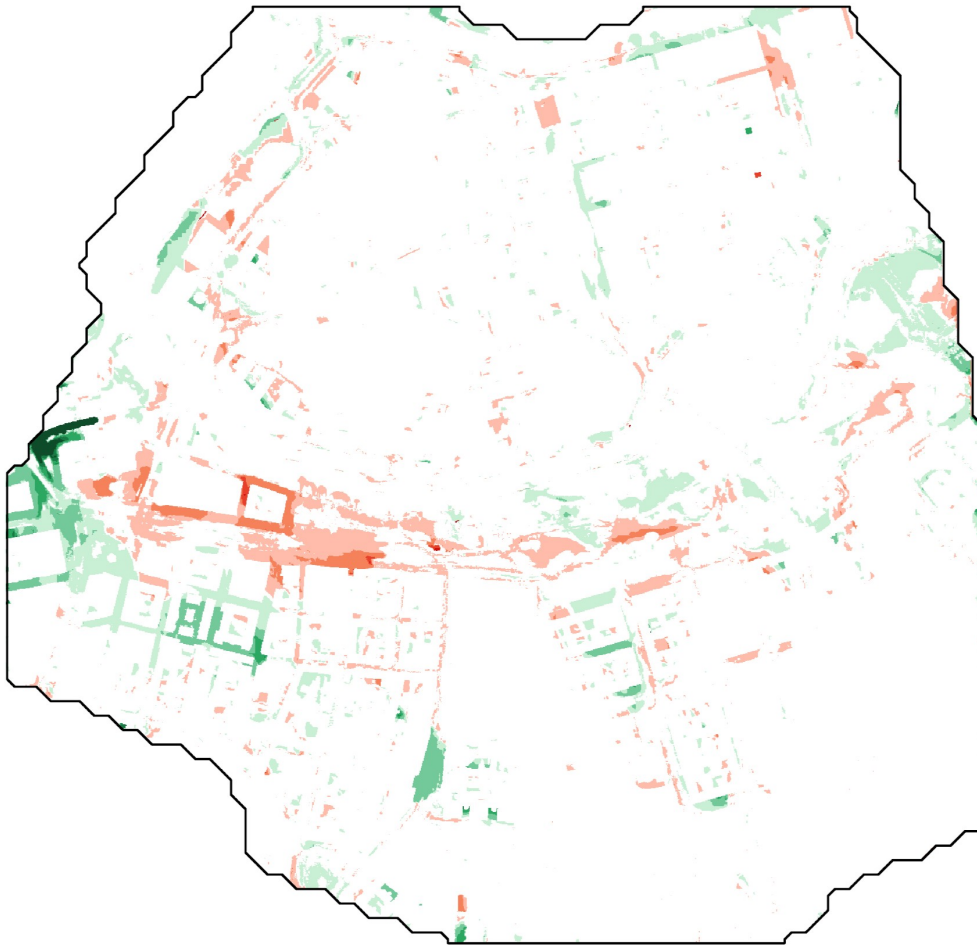




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Land Subsidence and Pluvial Flooding

Compounding Risks in Urban Environments - A Modelling Case Study of Gothenburg, Sweden

Master's Thesis in Infrastructure and Environmental Engineering

Alice Enbom & Ida Rastin

DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING
DIVISION OF WATER ENVIRONMENT TECHNOLOGY

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Master's Thesis in the Master's Program Infrastructure and Environmental Engineering
ALICE ENBOM & IDA RASTIN

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Cover: The cover presents the difference in maximum water depth between the two scenarios produced in MIKE+. Map produced in ArcGIS Pro by the authors. Further presented in Section 5.1.

Gothenburg, Sweden 2026

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Abstract

Cloudburst events are expected to increase in frequency and intensity due to climate change, posing growing challenges for urban flood management. While cities invest in hydrodynamic models and mitigation measures to address this risk, current assessments generally assume a stable ground surface, an assumption that may not hold in cities subject to ongoing land subsidence. Gothenburg, Sweden, is dominated by deep deposits of soft post-glacial clay that cause continuous land subsidence, yet subsidence is not currently included in hydrodynamic models or cloudburst risk assessments. This thesis investigates the impact of long-term subsidence on pluvial flood analysis through a case study in Gothenburg. Two 2D overland flow models were developed in MIKE+, simulated with a 100-year rainfall event. One model represents current terrain conditions, while the other incorporates subsidence-adjusted terrain projected 100 years into the future. By comparing the results of the two models, the influence of subsidence on flood outcomes was assessed. In parallel, a simplified risk assessment based on openly available data was conducted and evaluated as a potential tool for early identification of areas at risk, prior to a more detailed assessment being warranted. The results demonstrate that subsidence influences the spatial distribution of flooding, water depths, and flow paths. Existing flood-prone areas generally expand and deepen, while some areas show reduced exposure. The relationship between subsidence and flood response is non-linear and complex, governed primarily by the spatial variability of ground movement and its interaction with local topography rather than subsidence magnitude alone. The simplified risk assessment showed partial spatial correspondence with the modelling results, but subsidence magnitude alone proved an insufficient screening criterion. A more reliable assessment should examine the coincidence of low-lying terrain, deep clay deposits, and spatially variable subsidence. Taken together, the findings demonstrate that long-term subsidence is a relevant but currently overlooked factor in urban pluvial flood planning, and that integrating it into hydrodynamic models produces meaningful differences in simulated flood outcomes.

Keywords: cloudburst, hydrodynamic 2D overland flow model, land subsidence, MIKE+, pluvial flood

Marksättningar och skyfall

Kombinerade risker i urban miljö - En modelleringsfallstudie i Göteborg, Sverige

Alice Enbom & Ida Rastin

Institutionen för Arkitektur och Samhällsbyggnadsteknik

Avdelning för Vattenmiljöteknik

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Sammanfattning

Skyfall förväntas bli både vanligare och kraftigare till följd av klimatförändringarna, vilket ställer allt högre krav på städers förmåga att hantera översvämningar. Trots att städer investerar i hydrodynamiska modeller och skyddsåtgärder utgår nuvarande analyser i regel från att marknivån över tid är konstant. Det är ett antagande som inte stämmer i städer där marken kontinuerligt sätter sig. Göteborg domineras av djupa lager av mjuk postglacial lera som orsakar pågående marksättningar. Trots det beaktas inte sättningar varken i hydrauliska modeller eller skyfallsriskanalyser. Detta examensarbete undersöker hur långsiktiga marksättningar påverkar skyfallsanalyser genom en fallstudie i ett område i Göteborg. Två ytavrinningsmodeller togs fram i MIKE+, båda simulerade med ett 100-årsregn. Den ena modellen representerar nuvarande markförhållanden, medan den andra inkluderar en sättningsjusterad terrängmodell 100 år fram i tiden. Genom att jämföra resultatet från de två modellerna undersöktes hur marksättningar påverkar översvämningsbilden. Parallellt genomfördes och utvärderades en förenklad riskanalys baserad på öppet tillgängliga data som ett potentiellt verktyg för tidig identifiering av riskområden innan en mer detaljerad analys är motiverad. Resultaten visar att marksättningar påverkar översvämningsarnas rumsliga utbredning, vattendjup och flödesvägar. Befintliga problemområden tenderar att växa och få större vattendjup, medan vissa områden uppvisar minskad exponering. Sambandet mellan marksättning och översvämning är icke-linjärt och komplext. Det är främst den rumsliga variationen i markrörelser och samspelet med lokal topografi, snarare än sättnings storlek, som styr utfallet. Den förenklade riskanalysen visade partiell geografisk överensstämmelse med modelleringsresultaten, men enbart sättnings storlek visade sig vara ett otillräckligt kriterium. En mer tillförlitlig bedömning bör istället undersöka var låglänt terräng, djupa lerlager och rumsligt variabel marksättning sammanfaller. Sammantaget visar studien att långsiktig marksättning är en relevant men hittills förbisedd faktor i urban skyfallsplanering, och att en integrering av den i hydrodynamiska modeller ger betydelsefulla skillnader i simulerade översvämningsutfall.

Nyckelord: hydrodynamisk ytavrinningsmodell, marksättning, MIKE+, skyfall, översvämning.

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Alice Enbom and Ida Rastin, Gothenburg, May 2026

Declaration of AI

Artificial intelligence (AI) tools were used as support tools during the writing process of this thesis. AI was utilized for translation between Swedish and English, grammar and spell checking, LaTeX typesetting including table formatting in Overleaf, and Python code for generating diagrams. All AI-generated content has been reviewed, evaluated and revised by the authors, who take full responsibility for the accuracy and integrity of the final work.

Terminology

Below is a list of words that have been used throughout this thesis listed in alphabetical order:

100-year return period rainfall	- A rainfall event with a return period of 100 years, occurring on average once in 100 years, corresponding to a 1 % annual probability.
1D model	- A model that solves flow equations in one dimension. Used to calculate water levels, flow, and velocity in pipe networks and watercourses.
1D-2D coupling	- Enables interactions between a 1D and a 2D model.
2D model	- A model that solves flow equations in two dimensions. A 2D model calculates water levels, flow, and velocity on the ground surface.
2D overland	- A module in MIKE+ used for modelling 2D free-surface flows across the surface. Used in this thesis to model pluvial flooding.
Boundary conditions	- Defines the boundary of a flood model. Can describe discharge from the domain, water levels over time, and evaporation.
Chicago Design Storm (CDS)	- A type of synthetic rainfall event. Commonly used as precipitation input in pluvial flood modelling.
Climate factor	- A factor multiplied with the rain intensity to account for increase in rain intensity due to climate change.
Cloudburst	- High-intensity rainfall defined as at least 50 mm of rain in one hour or 1 mm in one minute.
Consolidation	- A time-dependent process in which water is gradually expelled from saturated soil under increased effective stress, leading to volume reduction and subsidence.
Design storm	- Synthetic rainfall event where precipitation data is not based on historical rain series.
Detailed analysis	- A level of accuracy at which a pluvial flood model is conducted using dynamic 2D modelling tools. The detailed analysis level provides accuracy considered sufficient for risk and consequence analysis, however applies some conservative assumptions to account for uncertainties introduced by model simplifications.
dfs-file	- File format associated with the MIKE-series.
Digital Elevation Model (DEM)	- A model over the terrain containing elevations of the surface. Used as topographic input in flood modelling.

Drainage network deduction	- A method used to account for the capacity of the underground stormwater pipe network in a 2D overland flow model. Rather than explicitly modelling the pipe network, its drainage capacity is represented as a reduction in the rainfall input.
Flux	- The volume of water passing through a cross-section per unit width per unit time, expressed as L/s/m.
Hydrodynamic (HD)	- Module within MIKE+ used to simulate flow in 2D overland.
Hyetograph	- A graph showing the temporal distribution of rainfall intensity during a storm event. Used as precipitation input in hydrodynamic models.
Infiltration module	- A model component that simulates the process by which rainfall is absorbed into the soil, reducing the volume of water available for surface runoff.
Initial conditions	- The state of the model at the start of a simulation, defining the initial water levels, flow velocities, and soil moisture content across the model domain before any rainfall input is applied.
InSAR (Interferometric Synthetic Aperture Radar)	- A satellite-based remote sensing method that detects ground surface deformation by comparing phase differences between repeated radar signals, with millimetre precision.
Intensity-Duration-Frequency (IDF) curve	- A statistical relationship describing the probability of rainfall of a given intensity occurring over a given duration and return period.
Inundation	- The covering of normally dry land with water, used interchangeably with flooding in this thesis.
Manning's roughness coefficient	- A parameter describing the roughness of a surface, used to quantify resistance to water flow.
Mean step accumulated time series	- Time series with average values valid between two time steps.
Meta-model	- A statistical model trained on multiple detailed simulations to extend predictions spatially across a larger area.
MIKE Zero	- Software developed by the Danish Hydrological Institute (DHI), used to create, process, and convert dfs-files.
MIKE+	- Hydrodynamic modelling software developed by the Danish Hydrological Institute (DHI), used in this thesis for 2D overland flow simulations.
PLAXIS 2D	- A finite element software used for geotechnical analysis.

Pluvial flood modelling	- A dynamic analysis using a hydraulic model that identifies which areas are inundated during a studied rainfall event and how these vary over time. The result is a map-based output showing flood extent, water depths, flow paths, and velocities.
Pluvial flooding	- Surface flooding caused by rainfall exceeding the drainage capacity of the ground and stormwater system, distinct from fluvial or coastal flooding.
Postglacial clay	- Soft, sensitive clay deposited after the last ice age, dominant in the Gothenburg subsurface and highly prone to consolidation and long-term subsidence.
Precipitation	- Condensed atmospheric water vapour that falls from clouds in the form of, for example, water or snow.
Rain intensity	- Amount of precipitation per unit of time. Often presented as mm/h.
Representative Concentration Pathways (RCP)	- Standardised greenhouse gas concentration trajectories used to project climate change outcomes under different future emission scenarios.
Return period	- The average time interval within which a rain event is expected to occur or be exceeded once.
Runoff coefficient	- The proportion of rainfall that becomes surface runoff rather than being absorbed by infiltration or evaporation.
Simplified risk assessment	- A GIS-based overlay analysis combining InSAR data, topography, and soil classifications to identify potential subsidence-affected flood zones without detailed hydrodynamic modelling.
Skewness factor	- A factor used to create a CDS rain event, describing where the maximum intensity of the rainfall will occur within the storm duration.
Stormwater	- Water that originates from precipitation and contributes to surface runoff or evaporates back into the atmosphere.
Subsidence	- A vertical lowering of the ground surface caused by consolidation of soils under load, groundwater extraction, or other anthropogenic and natural processes.
SWEREF 99 12 00	- A projected coordinate reference system used in Sweden, based on the SWEREF99 geodetic datum. Used to accurately represent positions in the western parts of Sweden, including Gothenburg, and used for all spatial data in this thesis.

Nomenclature

Below is the nomenclature of indices, parameters, and variables used in the precipitation modelling and construction of the CDS rainfall event as described by Olsson et al. (2017a) and Svenskt Vatten (2011).

Indices

t	Index for time step
-----	---------------------

Parameters

a_1, a_2, a_3	Empirical coefficients defining the return-period dependent function $k(T)$ [-]
b_1, b_2, b_3	Empirical coefficients defining the return-period dependent function $p(T)$ [-]
$k(T)$	Return-period dependent coefficient in the nested power rainfall model [-]
$p(T)$	Return-period dependent exponent in the nested power rainfall model [-]
$M(V)$	Scaling factor compensating for the fixed 15-minute measurement intervals of SMHI's automatic stations [-]
T	Return period [years]
V	Rainfall duration [minutes]
r	Skewness factor determining the relative timing of the peak intensity within the CDS event [-]
CF	Climate factor applied to rainfall intensity to account for projected future increases in precipitation [-]

Variables

R	Accumulated rainfall volume for a given duration and return period [mm]
I_t	Rainfall intensity at time step t [mm/h]
t_{peak}	Time of maximum rainfall intensity within the CDS event

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1. Introduction

Cloudburst events are expected to occur more frequently in the future due to climate change (Axelsson et al., 2021). Cloudbursts cause flooding, particularly in urban areas where natural land has been converted into impervious surfaces (Kyaw et al., 2024). More specifically, pluvial flooding occurs when the amount of rainfall exceeds the drainage capacity of the ground surface and drainage systems, typically manifesting as manhole overflows and water accumulation in low-lying areas. Floods impose substantial economic burdens on society through property damage and recovery costs (Hou et al., 2023), and can lead to negative social and environmental impacts, including psychological distress, physical illness, reduced biodiversity, and even loss of life (Sharma & Malaviya, 2021).

Cities must therefore be prepared for cloudburst events to prevent environmental damage, economic losses, and human health risks (Axelsson et al., 2021). Current mitigation strategies include physical measures such as traditional stormwater infrastructure and green infrastructure (Axelsson et al., 2021), as well as strategic measures, such as hydrodynamic flood models, that incorporate rainfall data and digital elevation models to identify risk zones and consequences in urban areas (Kyaw et al., 2024). Multiple sources (Axelsson et al., 2021; Hou et al., 2023; Kyaw et al., 2024; Wild et al., 2024) emphasize the continuous need for the development and advancement of flood mitigation strategies, and society must use assessment tools to prepare for floods in advance, helping communities predict, prevent, and reduce flood impacts.

In Gothenburg, Sweden, cloudburst management is governed by regulatory documents that require current cloudburst studies to assess future 100-year rainfall events to estimate flood depths and their potential impacts on buildings, accessibility, and emergency response (Kretslopp och vatten, 2021a). These studies, referred to as structural plans, analyse socio-economic consequences using hydrodynamic models with a climate factor to ensure safe elevation of buildings and roads. Input data include elevation models, hydraulic pipe network models, watercourse models, rainfall statistics, land use information, soil maps, and the city’s primary map (Kretslopp och vatten, 2021b). Early in urban development processes, prioritised roads and emergency routes must be identified and designed with adequate cloudburst management facilities, with accumulated water depths not exceeding 0.2 metres on prioritised routes (Göteborgs Stad, 2019).

These analyses generally rely on elevation data and surface characteristics that assume that the ground level remains unchanged over time. However, Gothenburg is dominated by deep deposits of soft sensitive glacial and post-glacial clays, which together with large amounts of fill material deposited during the city’s expansion cause continuous land subsidence (Tornborg et al., 2021). This results in a gradual lowering of the ground surface, particularly where load is applied, as is the case in urban environments with buildings and roads. Long-term subsidence combined with heavy rainfall could mean that elevations of roads and buildings deemed safe according to current standards may no longer serve their intended purpose in the

future. Despite this, subsidence is not currently included in hydrodynamic models or cloudburst risk assessments, meaning that there is a risk of underestimating and incorrectly predicting future flow paths and flood-prone areas.

Thus, one potential advancement involves the integration of subsidence into flood models to better capture the combined effects of cloudburst and subsidence in urban environments. This master's thesis evaluates the impact of long-term subsidence on pluvial flooding through hydrodynamic modelling in a case study in Gothenburg, Sweden. To achieve this, a hydrodynamic analysis using MIKE+, comparing flood simulations with and without subsidence-adjusted terrain, is carried out. In addition, a simplified risk assessment is conducted, examining whether readily available data sources, such as InSAR-derived subsidence measurements, topographic data, and soil classifications, can serve as a first-stage assessment tool in early planning, indicating whether a hydrodynamic analysis incorporating subsidence is warranted. The performance of this simplified risk assessment is evaluated by comparing its findings with the results of the modelling.

1.1 Aim

The aim of this thesis is to investigate the impact of long-term subsidence on pluvial flood analysis and urban flood resilience planning, and to identify conditions under which subsidence becomes a relevant factor in urban cloudburst management. The potential of a simplified risk assessment as a first-stage screening tool for identifying such conditions will also be evaluated.

1.2 Objectives

Following the aim, the thesis addresses the following research objectives:

1. Develop two 2D overland flood models of the study area, one with the current terrain and one with subsidence-adjusted terrain, as a basis for assessing the influence of subsidence on pluvial flood outcomes.
2. Investigate if and how the inclusion of subsidence in hydrodynamic models affects the spatial distribution of flooding, water depths, and flow paths during cloudburst events.
3. Investigate whether low-lying areas underlain by subsidence-prone soils and subject to significant subsidence are systematically more exposed to increased flood depths and altered flow paths than areas where these conditions are absent or less pronounced.
4. Evaluate whether a first stage simplified risk assessment can reliably indicate areas where subsidence is likely to influence pluvial flood outcomes, and whether such an approach can serve as a first-stage assessment tool prior to hydrodynamic modelling.

1.3 Limitations

This study has limitations that define its scope. The analysis is geographically limited to a specific area in Gothenburg, for which existing subsidence data was available. No independent subsidence analysis was conducted as the subsidence data was taken directly from an existing meta-model developed for the study area. As the Gothenburg subsurface is dominated by thick clay deposits, the findings are

primarily representative of subsidence in clay, and may not be directly transferable to areas with different soil conditions.

The study focuses exclusively on pluvial flooding, defined as surface flooding caused by rainfall exceeding the drainage capacity of the ground and stormwater system. Other flood types, such as fluvial or coastal flooding, fall outside the scope of this study. The hydrodynamic modelling was conducted using a strict 2D overland flow model, without coupling to a 1D pipe network model or a watercourse model. Furthermore, rainfall data specific to Gothenburg was not available, and generalised CDS rainfall for the south-western part of Sweden was used instead. The analysis is based solely on a single rainfall event with a 100-year return period, and the results are therefore not representative of other rainfall magnitudes or durations.

Finally, the simplified risk assessment relies on InSAR data reflecting historically observed ground movement rather than projected future subsidence, which introduces uncertainty when used as a proxy for long-term subsidence patterns.

2. Theory

The following chapter provide a theoretical background to pluvial flooding, subsidence, and pluvial flood modelling, both in general and in MIKE+. Previous studies on the combined effects of subsidence and pluvial flooding are also reviewed. An understanding of the these topics and their interactions provides a solid foundation to address the objectives and for the modelling approach applied in this study.

2.1 Pluvial flooding

Flooding has been classified as the most common natural disaster, associated with 49% of the total affected population (Figueroa-Miranda et al., 2025). Pluvial floods occur in urban environments where the lack of permeability of the land surface causes stormwater to accumulate or flow overland (Jha et al., 2012). Heavy rainfall can exceed the capacity of stormwater drainage systems, resulting in flooding, particularly in low-lying areas. Pluvial floods are an increasing global problem, driven by the intensification of extreme precipitation events under climate change and the expansion of impervious surfaces through rapid urbanisation (Yin et al., 2016). Climate change contributes to more frequent and intensified extreme weather events, such as cloudbursts (He et al., 2025). The Swedish government agency under the Ministry of Climate and Enterprise defines a cloudburst as at least 50 mm of rain in one hour or at least 1 mm per minute (SMHI, n.d.). Predictions indicate that the frequency of extreme flood events in Europe, with a return period that exceeds 100 years, is expected to double on average by 2035 due to climate change (He et al., 2025). Further on, urbanisation exacerbates pluvial flooding by reducing hydraulic areas, increasing flow velocity on narrow streets, and hindering natural drainage paths, leading to flow accumulation (Figueroa-Miranda et al., 2025). More broadly, changes in land use and land cover, such as deforestation, urbanisation, and wetland loss, are known to increase flood frequency by altering infiltration, groundwater recharge, surface runoff, and baseflow (Darmola et al., 2022; Ndulue et al., 2015; Oo & Humphries, 2025). A key indicator of this relationship is the runoff coefficient, which describes the proportion of rainfall that becomes surface runoff. Land use strongly influences the runoff coefficient through its effect on soil type, vegetation, slope, and permeability (Machado et al., 2022). In urban areas, runoff coefficients can vary notably over short distances, further increasing the risk of pluvial flooding.

The prediction of more frequent cloudbursts leading to pluvial flooding has prompted the implementation of stricter stormwater design criteria in Sweden (Svenskt Vatten, 2026). The goal of these criteria is to increase the resilience of the society to floods and to reduce the environmental impact of stormwater, with two key requirements being safe building elevations and adequate pathways for stormwater runoff (Svenskt Vatten, 2016). To meet these criteria, flood risk management strategies typically combine structural and non-structural measures (Jha et al., 2012). Structural measures range from heavily engineered solutions, such as drainage channels and reservoirs, to more nature-based approaches, such as wetlands and green infrastructure. Non-structural measures, on the other hand, rely on a thorough under-

standing of flood hazard rather than physical infrastructure, and include land use planning, early warning systems, and emergency management. In practice, flood risk management strategies commonly combine dedicated stormwater pathways, retention areas, and blue-green solutions to buffer larger volumes of runoff (Jha et al., 2012; MSB, 2016). More recently, scenario analysis and pluvial flood modelling have emerged as central tools in this context (Navarro-Hernandez et al., 2023). Identifying where and how flooding occurs is a prerequisite for designing such measures effectively (Svenskt Vatten, 2016). Incorporating flood modelling early in the urban planning process allows planners to delineate flood-prone areas and evaluate management strategies before implementation, which can also help keep costs reasonable (Svenskt Vatten, 2016, 2026).

2.1.1 Impacts of pluvial flooding

Pluvial flooding can result in a wide range of consequences, spanning economic, social, and environmental domains (Axelsson et al., 2021; Hou et al., 2023; Pamuru et al., 2022; Zhang et al., 2024). The severity of these consequences depends on several factors, including the volume and intensity of precipitation, the characteristics of the affected area, and the capacity of drainage systems, watercourses, and other pathways to manage excess water (MSB, 2013, 2020). Topographic conditions, the location of populated areas relative to watercourses and low-lying terrain, and the overall preparedness of the affected community also play a significant role in determining outcomes (MSB, 2020). Furthermore, a general increase in societal vulnerability, partly due to the placement of sensitive buildings and infrastructure in unsuitable locations, has contributed to a growing trend of increasing consequences from extreme weather events such as cloudbursts in both Sweden and Europe. These consequences can broadly be categorised as direct or indirect, and as tangible or intangible (MSB, 2013). Direct consequences refer to damages caused immediately by the cloudburst event itself, such as physical damage to buildings, while indirect consequences are those that can be linked to the event but not directly caused by it, such as traffic disturbances. Tangible consequences are those that can be expressed in monetary terms, while intangible consequences cannot be quantified financially, such as health effects, psychological harm, and ecosystem damage, making them considerably more difficult to assess than direct structural damage.

Flood events can lead to substantial financial losses through direct damage to buildings, infrastructure, and assets, particularly in densely populated urban areas (Axelsson et al., 2021; Hou et al., 2023). Direct costs include damage to structures and their contents, while indirect consequences such as power outages, disrupted transport, and business interruptions can compound the economic impact (MSB, 2020). Property values in areas prone to repeated flooding may also decline over time (Axelsson et al., 2021; MSB, 2013). Many businesses and public services risk being unable to maintain full operations, and may face additional costs as a result (MSB, 2020). Additionally, in agricultural contexts, cloudbursts can result in significant economic losses for farming enterprises through reduced yields, soil damage, and increased labour and production costs. The breadth of these economic consequences is illustrated by the cloudburst event in Gävle, Sweden, in August 2021, during which 161.6 mm of rainfall was recorded over 24 hours, including 101

mm within a single two-hour period (Länsstyrelsen Gävleborg, 2022). The event caused extensive damage to both private and public property, and agricultural land, with an estimated 4,000 to 5,000 buildings affected and total direct costs estimated at between 500 and 1,000 million Swedish kronor.

Beyond economic impacts, psychological and physical trauma are among the most prominent social consequences of flooding (Hou et al., 2023). Health risks include injury, the spread of infectious disease, and strain on healthcare systems due to increased demand, absent staff, and disrupted transport (MSB, 2013, 2020). Emergency services may face increased operational pressure, and in severe events, access to affected areas can be significantly impeded (MSB, 2020). Transport disruptions represent another significant social consequence, with closures and lengthy diversions affecting emergency vehicles, home care services, school transport, business deliveries, and regional traffic (MSB, 2020). Critical infrastructure is also at risk. Power, gas, and telecommunications networks may fail due to flooding or associated lightning strikes, and underground cables can be damaged by water ingress. The vulnerability of critical societal functions is illustrated by the cloudburst event in Copenhagen in July 2011, during which approximately 150 mm of rainfall was recorded within two hours (MSB, 2020). Among the most severe consequences was structural damage to Rigshospitalet, one of Denmark’s leading hospitals, highlighting how cloudburst events and flooding can threaten the continuity of vital healthcare services (MSB, 2016).

Stormwater generated when rainfall contacts impervious surfaces mobilises a range of pollutants, including nutrients, metals, particulate matter, toxic organic compounds, and microorganisms (Pamuru et al., 2022). When discharged into receiving water bodies, these pollutants can reduce water quality and pose risks to both human and aquatic life. Floods can further cause leakage from hazardous industrial sites and inundate old landfills and contaminated land, spreading pollutants into the surrounding environment (MSB, 2020). High-velocity floods cause greater erosion and damage to vegetation, while deeper floods allow water to interact with more pollution sources (Zhang et al., 2024). Overloaded combined sewer systems may also cause untreated wastewater to back up into buildings, creating sanitary hazards (MSB, 2020).

Taken together, these consequences highlight the multifaceted risks associated with pluvial flooding and underscore the importance of proactive urban planning and flood risk management.

2.1.2 Stormwater regulation in Sweden

Stormwater management in Sweden is not governed by a single regulatory framework, but rather by the interplay of several pieces of legislation, primarily the Planning and Building Act (Plan- och bygglag, SFS 2010:900), the Environmental Code (Miljöbalk, SFS 1998:808), the Land Code (Jordabalk, SFS 1970:994), and the Act on Public Water Services (Lag om allmänna vattentjänster, SFS 2006:412) (Sveriges riksdag, 1970, 1998, 2006, 2010).

Municipalities bear the primary responsibility for addressing cloudburst risks in new development (Sveriges riksdag, 2010). The Planning and Building Act states that detailed development plans must be assessed from a climate adaption per-

spective, including risks associated with cloudbursts and flooding, to ensure that proposed developments are feasible. Municipalities that fail to adequately account for cloudburst risks may face both plan revocation by the County Administrative Board and liability for flood damage. The Environmental Code (Sveriges riksdag, 1998) classifies stormwater draining from detailed plan areas as wastewater, subject to treatment requirements, a principle also stated in the Act on Public Water Services (Sveriges riksdag, 2006), under which stormwater discharged from contiguous built-up areas carries the same classification. Municipalities are obligated to establish service areas and ensure that necessary infrastructure is in place, while the water utility bears the operational responsibility for managing stormwater. However, both laws explicitly exclude cloudburst water from the definition of wastewater, meaning that cloudburst management falls outside the scope of these regulations. Nonetheless, stormwater infrastructure can be coordinated with cloudburst management facilities.

However, the regulatory framework is considerably less clear when it comes to existing built environments. Under the Planning and Building Act, municipalities are required to assess and address risks to the built environment posed by climate change through strategic planning, including the comprehensive plan (Sveriges riksdag, 2010). Yet, while municipalities carry a strategic planning obligation, the responsibility for implementing physical climate adaptation measures on existing properties falls on individual property owners under the Land Code (Sveriges riksdag, 1970). As a result, older urban districts that predate modern stormwater requirements may lack adequate infrastructure, despite the municipality's broader planning obligations.

While legal responsibility for cloudburst management remains fragmented, several authorities and organisations play supporting roles (MSB, 2022; Salomonsson et al., 2017). The Swedish Civil Contingencies Agency (MSB, now reorganised as the Swedish Agency for Civil Defence, MCF) plays a central role at the national level, responsible for flood modelling, developing guidance for flood modelling, and identifying areas of significant flood risk in accordance with the EU Floods Directive (MSB, 2022). MSB also maintains emergency resources such as barriers and pumps, though these are primarily intended for prolonged or complex events rather than rapidly developing cloudbursts. The County Administrative Boards hold the broadest formal mandate, overseeing municipal physical planning, emergency preparedness, and water management (MSB, 2022; Salomonsson et al., 2017). They are responsible for reviewing municipal detailed plans with respect to flood risks, and for producing flood risk maps and management plans for identified risk areas under the EU Floods Directive. Boverket provides supervisory guidance to the County Administrative Boards regarding flood risk in municipal detailed plans, and maintains planning guidance through its online knowledge portal (Boverket, n.d.). Svenskt Vatten, while lacking a formal mandate, plays a significant role through its technical publications, which have been repeatedly referenced by Swedish courts and are widely applied as industry standards (Salomonsson et al., 2017). Taken together, while guidance and institutional support exist, there remains no single authority with a clear national mandate to drive cloudburst planning in Sweden (Salomonsson et al., 2017).

2.2 Subsidence

Subsidence describes a vertical lowering of the ground surface that may occur either gradually over long periods or more abruptly (Bagheri-Gavkosh et al., 2021). Subsidence can take place both locally and over large regional scales (Huning et al., 2024). The phenomenon is primarily associated with the consolidation of sediments caused by an increase in effective stress within the ground (Wikby et al., 2025). However, subsidence is driven by both natural processes, including long-term creep and tectonic deformations, and anthropogenic activities, such as construction-induced loading and the extraction of natural resources, particularly groundwater (Huning et al., 2024; Wikby et al., 2025). In many regions, anthropogenic influences have been documented as the dominant driving force of observed subsidence (Huning et al., 2024). Urbanisation and urban development can lead to compaction of underlying soils, especially if the newly applied loads exceed the maximum historical stress experienced by the soil. Under such conditions, consolidation and subsidence may occur as a response to altered loading patterns. Consequently, urban areas underlain by thick deposits of soft soils are particularly vulnerable to subsidence (Wikby et al., 2025). Subsidence poses a significant threat to urban environments as it can cause extensive infrastructure damage, environmental degradation, and societal impacts (Huning et al., 2024). In addition, subsidence is increasingly recognized as an important factor influencing urban pluvial flooding (Figuerola-Miranda et al., 2025; Navarro-Hernandez et al., 2023; Yin et al., 2016). By altering terrain morphology, subsidence can modify local flow paths and runoff patterns, thereby increasing the risk of surface flooding. This is further explained in Section 2.3.

2.2.1 Measuring and predicting subsidence

Subsidence can be measured and monitored through a range of methods, broadly categorised as ground-based and remote sensing approaches (Bagheri-Gavkosh et al., 2021). Ground-based methods, such as precise levelling, GPS surveys, and extensometry, measure relative changes in land surface altitude by referencing stable benchmarks. While these methods can provide accurate local measurements, they are generally time-consuming, labour-intensive, and limited in spatial coverage. Remote sensing techniques, particularly satellite-based radar methods, have therefore become increasingly prevalent, offering the ability to monitor surface deformation across large areas with millimetre to centimetre precision (Bagheri-Gavkosh et al., 2021). Among these, InSAR detects surface deformation by comparing radar signals recorded during repeated passes of the satellites over the same location (Swedish Geotechnical Institute, 2026b). By analysing phase differences between signals, vertical displacements can be identified with millimetre precision over time. However, it is important to note that the data represents relative, rather than absolute, movement and should be interpreted as an estimation rather than a direct measurement.

While measurement techniques capture the observed ground movement, predicting future subsidence requires either extrapolation of existing displacement data or physically based numerical modelling (Figuerola-Miranda et al., 2025; Wikby et al., 2024). One approach involves extending InSAR-derived displacement rates over future time horizons, assuming a linear subsidence trend (Figuerola-Miranda et al., 2025). This method uses interpolated vertical displacement rasters derived

from InSAR time series to project cumulative subsidence over future periods. While computationally accessible, this approach assumes that observed subsidence rates remain constant over time, which may not hold in areas where subsidence is driven by time-dependent processes such as clay creep (Tornborg et al., 2021). A more physically based alternative involves geotechnical numerical modelling, which simulates the deformation behaviour of soils under loading, accounting for consolidation and time-dependent creep processes (Wikby et al., 2024). Such models can account for soil stratigraphy, groundwater conditions, and time-dependent deformation processes, and are typically calibrated against borehole data and laboratory tests. To extend predictions spatially across larger areas, statistical meta-models trained on multiple cross-sectional simulations can be employed to upscale results.

2.3 Studies on subsidence and flood risk

Land subsidence and its influence on flood dynamics has been investigated across several regions, with studies consistently showing that subsidence alters local topography in ways that affect flood depths, inundation patterns, and flow velocities. Two of the more foundational studies were conducted in Shanghai and Houston (Jiang et al., 2023; Yin et al., 2016). Yin et al. (2016) quantified inundation patterns over four time periods using subsidence rates of 27 mm/year derived from levelling and airborne LiDAR data, with measured rainfall from a historical storm event corresponding to a 30-year return period as precipitation input. Jiang et al. (2023) similarly examined retrospective subsidence in Houston, though over a longer time-frame and with considerably higher cumulative subsidence magnitudes. Despite the difference in subsidence rates and regional context, both studies found that the direct impact on flood depths was relatively modest. However, both identified a non-linear relationship between subsidence and flood response, where spatially variable subsidence rates modify local and watershed-scale elevation gradients over time, causing flood hotspots to shift or relocate rather than simply intensify in place. Yin et al. (2016) further concluded that the local flood response is more strongly governed by relative relief than by the absolute magnitude of subsidence. Spatially variable subsidence rates can modify local and watershed-scale elevation gradients, leading to shifts in flood-prone areas and changes in inundation patterns. This is a finding consistent with the results of Jiang et al. (2023), suggesting that terrain characteristics play a central role in mediating the effects of subsidence.

This relationship between terrain and subsidence impact is further illustrated by the study of the Alto Guadalentín Valley in Spain by Navarro-Hernandez et al. (2023), where cumulative subsidence of up to 2.7 m between 1992 and 2016, quantified using InSAR data from multiple datasets, led to more pronounced changes in flood characteristics than those observed in Shanghai and Houston. The substantially greater subsidence magnitude, combined with the more varied terrain of the valley, meant that topographic changes had a stronger influence on flood extent, water depth, and flow velocity. Flood scenarios were evaluated using a constructed design storm corresponding to a 100-year return period, rather than a historical event. Notably, subsidence was found to reduce flow velocities by creating more depressed terrain, thereby worsening natural drainage conditions and increasing inundation duration. This reinforces the conclusion from earlier studies that terrain

morphology is a key determinant of how subsidence translates into flood risk, while also suggesting that the magnitude of subsidence itself becomes more consequential in less flat environments.

More recent studies have gone beyond retrospective analysis to consider how subsidence interacts with future urban development and climate change. Figueroa-Miranda et al. (2025) examined Morelia, Mexico, where subsidence scenarios for 2017 and 2050 were constructed by combining InSAR measurements with LiDAR-derived topography and extrapolating forward assuming a linear subsidence rate. All scenarios used the same constructed design storm with a 50-year return period. The study found that while urban growth and future subsidence reduced the total flooded area, it simultaneously increased flooding severity in vulnerable zones, highlighting the compounding effect of subsidence and urbanisation. High risk zones were identified as low-lying subsidence-prone areas, densely urbanised areas, and the banks and mouths of streams. In the Linbian River Basin in southern Taiwan, Chen and Tfwala (2018) investigated a setting with comparatively lower subsidence magnitudes, ranging from less than 10 cm to just over 60 cm, but showed that even at these scales the combined effects of subsidence and a worst-case climate change scenario increased both inundation depth and duration across a wide range of constructed storm events with return periods from 2 to 200 years.

Taken together, the literature demonstrates that subsidence influences flood dynamics in a non-linear manner, with impacts that depend on terrain characteristics, subsidence rates and magnitudes, the type of rainfall input used, and the broader urban and climatic context. This underscores the importance of incorporating subsidence into flood risk assessments, particularly as urban areas continue to develop and climate change drives more intense rainfall events.

2.3.1 Knowledge gap

While previous studies have advanced the understanding of how subsidence shapes flood dynamics, several important gaps remain. Research has primarily focused on regions outside Northern Europe, and there is limited knowledge of how subsidence interacts with pluvial flooding in cities such as Gothenburg, Sweden, where specific soil conditions and low-lying urban areas may create distinct vulnerabilities. Existing studies have also been largely retrospective, examining how historical subsidence and past rainfall events have influenced flood depths and inundation patterns, but rarely considering how future subsidence trajectories and climate-change-driven increases in cloudbursts might interact over time (Jiang et al., 2023; Navarro-Hernandez et al., 2023; Yin et al., 2016). Few studies have incorporated advanced predictive subsidence models, leaving a gap in understanding how evolving ground conditions and intensified rainfall could affect future flood risks and urban planning decisions (Chen & Tfwala, 2018; Figueroa-Miranda et al., 2025). Furthermore, there is little guidance on how subsidence affects practical stormwater design criteria, safe building elevations, and flood pathways, or on whether subsidence should always be considered in pluvial flood modelling, or only under specific geotechnical or urban conditions.

This study addresses these gaps by providing region-specific insights for Gothenburg, combining long-term subsidence projections derived from geotechnical meta-

modelling with climate-adjusted design storms in MIKE+ to assess how future subsidence influences pluvial flood risks. By evaluating flood depths, pathways, and design criteria, it offers practical guidance for more resilient stormwater management and contributes to a currently under-represented area of research.

2.4 Pluvial flood modelling

Pluvial flood modelling encompasses a range of approaches, and the selection of an appropriate method depends on the available data, the objectives of the study, and the required level of accuracy (MSB, 2023). Pluvial flood modelling approaches can broadly be categorised as static or dynamic. Static tools indicate where water may accumulate and require relatively low effort, but risk both over- and underestimating the real flood risk. They are therefore not recommended for risk and consequence analyses, dimensioning of measures, or spatial planning. Dynamic tools additionally describe how water moves through the terrain over time, where the result of each time step serves as input to the next, making them more suitable for detailed analyses.

Depending on the required accuracy, three levels of analysis can be distinguished (MSB, 2023). A simplified analysis relies on static tools and provides only a rough estimate of flood risk. A detailed analysis employs dynamic models and provides accuracy sufficient for most practical applications, including risk and consequence analyses and spatial planning. An in-depth analysis also employs dynamic models but requires higher accuracy in model construction, and is recommended when the pipe network or watercourses are expected to have a significant influence on the result, or when dimensioning of specific measures is required. The choice between these levels involves a trade-off between accuracy and computational effort, and should be guided by the specific objectives and constraints of the study.

Dynamic pluvial flood models are commonly developed using physically-based modelling approaches, which simulate flood processes based on physical laws such as mass balance and conservation of momentum, rather than statistical relationships (Anuruddhika et al., 2025). This allows for detailed representations of flood extent and dynamics, and makes physically-based models well suited for analysing complex flow interactions and spatially distributed flooding processes. Physically-based models can be developed as one-dimensional (1D), two-dimensional (2D), or coupled 1D-2D models. 1D models use discrete cross-sections to describe water flow along one axis and are primarily used to represent rainfall-runoff processes and predict river discharge, but are limited in their ability to represent lateral flow processes (Anuruddhika et al., 2025). 2D models simulate flow in both the longitudinal and lateral directions, enabling greater spatial representation of flow patterns and inundation across the floodplain, making them particularly well suited for urban environments and areas with complex topography. Coupled 1D-2D models integrate both approaches, explicitly accounting for water exchange between pipe networks, watercourses, and the floodplain, thereby providing the most comprehensive representation of pluvial flooding.

Regardless of the modelling approach selected, several practical considerations should inform the setup of a pluvial flood model (MSB, 2023). The entire natural catchment area should be considered when defining the geographical boundaries of

the model, as it is not appropriate to limit the study to administrative areas or technical catchment boundaries alone. Where the model is simplified with respect to runoff from upstream catchment areas, it must be demonstrated that the method produces reliable results, or that safety margins and sensitivity analyses have been applied to address the associated uncertainties. For detailed and in-depth analyses, rain events with a return period of no less than 100 years are recommended as the primary design scenario (MSB, 2023). A higher water volume reduces uncertainties related to the influence of the pipe network and infiltration, both of which have a proportionally greater impact during smaller rain events and therefore need to be characterised with greater accuracy. Where a 2D model is not coupled with a 1D model, a standard deduction can be applied, in which a portion of the rainfall load is assumed to be drained by the stormwater system. The deduction can be distributed either temporally, spread over the duration of the rain event, or spatially across the model area. When applied spatially, the deduction is typically assigned only to impervious surfaces, reflecting that pervious surfaces absorb rainfall through infiltration rather than directing it to the pipe network. However, this approach is not appropriate in all situations and should be avoided when downstream urban areas are simultaneously studied, or where topographic conditions may cause water to be forced up through the pipe network. If the urban area being modelled is adjacent to watercourses, it should be assessed whether these need to be included in the pluvial flood model (MSB, 2023). Where the watercourse contains flow-obstructing structures such as culverts or bridges, or where it is otherwise expected to have a decisive influence on flood propagation, the pluvial flood model should be linked to a dedicated watercourse model. Where such detailed representation is not warranted, an alternative is to adjust the elevation model by assigning water surface levels based on measurements, as watercourses are often poorly represented in standard elevation models.

The input data required for pluvial flood modelling varies depending on the selected modelling approach (Anuruddhika et al., 2025). The following sections describe the key input components relevant to 2D pluvial flood modelling, including precipitation characteristics, climate factor, topography, infiltration processes, and surface roughness.

2.4.1 Precipitation

Precipitation is a key input in pluvial flood modelling and is used to simulate how rainfall generates surface runoff and urban flooding (Svenskt Vatten, 2011). To be applied in pluvial flood modelling, precipitation data must be expressed as a hyetograph, which describes the temporal distribution of rainfall intensity during a storm event. Two main types of precipitation data are commonly used: historical rainfall events and synthetic storms. Historical rainfall is based directly on measured precipitation data and can be presented as either rainfall intensity or rainfall volumes over a specific time interval. In contrast, a synthetic storm is an artificially constructed rainfall event developed specifically for modelling and design purposes.

A commonly applied synthetic rainfall pattern in pluvial flood modelling is the Chicago Design Storm (CDS) (Balbastre-Soldevila et al., 2019; Svenskt Vatten, 2011). A CDS is derived from intensity-duration-frequency (IDF) curves, which

describe the statistical relationship between rainfall intensity, duration, and return period. The concept of return period is central in defining the magnitude of both historical and synthetic storms used in flood modelling (Svenskt Vatten, 2011). The return period represents the statistical probability of a rainfall event of a given magnitude occurring in any given year, rather than at fixed intervals. Longer return periods correspond to lower probabilities and are often used to establish design and safety standards for urban drainage systems and flood protection measures. Rainfall duration further influences return periods, as short-duration storms with the same total volume generally correspond to longer return periods than longer-duration events. By combining rainfall intensities for different durations from an IDF curve, a single theoretical storm is generated, often representing more extreme rainfall than historically observed events of the same return period. The timing of the peak rainfall intensity is defined by a skewness factor, which determines where within the storm the maximum intensity occurs (Svenskt Vatten, 2011). A skewness factor of $r=0.5$ places the peak at the midpoint of the storm, while lower or higher values shift the peak toward the beginning or end of the event respectively, producing an asymmetric hyetograph.

In Sweden, IDF statistics have historically been derived from the rainfall analysis published by Dahlström (MSB, 2023), which provided national estimates of rainfall intensity as a function of duration and return period. Regionalised rainfall statistics that incorporate a more extensive observation record and account for spatial variation in precipitation climatology across the country were developed by SMHI in 2017 (Olsson et al., 2017b). The regionalised precipitation data are divided into four geographical zones (MSB, 2023). The Dahlström values tend to overestimate rainfall intensities relative to the more recent SMHI statistics and may therefore produce unrealistically extreme flood events.

The choice of precipitation input, including the source of IDF statistics, the type of design storm, and the storm duration, is not governed by a unified national standard in Sweden (MSB, 2023). Therefore, these decisions are made based on local practice, project requirements, or available data, and may vary between municipalities and consultants. However, it is recommended to apply current precipitation statistics in pluvial flood modelling according to MSB (2023), as the choice of rainfall input directly affects simulated flood extents and water depths, and consequently the conclusions drawn regarding flood risk.

2.4.2 Climate factor

Climate change is progressing rapidly and has been shown to increase both the intensity and the frequency of cloudburst events (Sjökvist et al., 2025; Svenskt Vatten, 2016). As precipitation patterns change, extreme short-duration rainfalls are expected to become more severe, posing increasing challenges for urban drainage systems and pluvial flood management. Climate models are therefore widely used to project future precipitation characteristics under different emission scenarios and time horizons, providing an important basis for climate-adapted pluvial flood mapping.

Intergovernmental Panel on Climate Change (IPCC) (2021) has developed four Representative Concentration Pathways (RCPs), ranging from a stringent mitigation scenario to one with very high greenhouse gas emissions. Using the intermediate

and high-emission scenarios, precipitation during cloudburst events in Sweden is estimated to increase by 20-40 % by the end of the century (Sjökqvist et al., 2025). To account for this projected increase, a climate factor is typically applied to the rain intensity in flood assessments, where a climate factor of 1.40 implies an expected increase in rainfall intensity of 40 % (MSB, 2023). The appropriate climate factor depends on the return period, rainfall duration, chosen emission scenario, and planning time horizon, and should therefore be selected carefully to reflect the conditions relevant to the assessment at hand. Recommended climate factors for Sweden range from 1.10 for the near future under moderate emission scenarios to 1.40 by the end of the century under high-emission scenarios (MSB, 2023).

2.4.3 Topography

Topography is used in pluvial flood modelling to identify confined areas and flow paths for runoff (Svenskt Vatten, 2016). Topography is fundamentally characterized by elevation and slope, which govern surface gradients and control water movement (Ouma & Tateishi, 2014). Slope determines both the direction and amount of surface runoff, influencing how rainfall contributes to streamflow. Floods are more likely to appear in areas with low gradient slopes as the stormwater can accumulate in these areas. Topography is normally included in flood mapping as a Digital Elevation Model (DEM), which is a three-dimensional digital simulation of the Earth's surface at the time of the data collection (Chindo, 2025). A DEM consists of a raster grid where each cell is assigned an elevation value, and its resolution determines the level of detail in the flood modelling results (MSB, 2014).

In urban environments, the DEM often requires adjustments to accurately represent structures that influence water transport (MSB, 2023). Buildings, roads, bridges, tunnels, culverts, and barriers all affect surface runoff and should either be incorporated into the DEM or otherwise accounted for in the model. Buildings not already represented in the DEM should be raised relative to the surrounding terrain, and roof surfaces should be flat or slope outward to avoid trapped water volumes. Smaller structures such as noise barriers, walls, and fences may fall below the resolution of the DEM but can still have a significant impact on flow paths in urban areas, and should therefore be identified through field surveys. Water surfaces, such as lakes and larger watercourses, should also be verified and corrected in the DEM where necessary.

2.4.4 Infiltration

Accurate soil infiltration data are crucial for creating realistic flood models (Frieze, 2025). In the context of pluvial flood modelling, it is the infiltration capacity of the unsaturated zone that is of primary interest (MSB, 2023). In this zone, water transport occurs vertically, whereas in the saturated zone, flow moves horizontally. Infiltration capacity is influenced by a range of factors (Frieze, 2025; MSB, 2023). Soil type is a key determinant, as different soils have different grain sizes and moisture retention properties that affect how water is absorbed. Land use, vegetation, topography, groundwater levels, and seasonal variations also affects the infiltration capacity (MSB, 2023). In urban areas, soil is typically more compacted than undisturbed natural ground, reducing infiltration capacity. Steeper slopes and high

groundwater levels further limit the soil’s ability to absorb water.

For detailed and in-depth analyses, infiltration is represented through an infiltration module, which typically incorporates parameters such as infiltration capacity, porosity, leak rate, soil depth, and degree of saturation (MSB, 2023). In Sweden, these parameters are typically derived from the Swedish Geological Survey’s (SGU) soil map. However, this data should be applied with caution in densely built urban areas, where the uppermost soil layer has often been replaced by material such as topsoil or fill, and where human activity has likely resulted in greater soil compaction than in natural areas. Several methods exist for simulating infiltration within such a module, with Green-Ampt, Horton, and Initial Loss/Continuing Loss being among the most common formulations.

Since infiltration conditions are often uncertain, it is recommended to conduct cloudburst modelling both with and without infiltration, providing a sensitivity analysis of how much infiltration affects the results (MSB, 2023). Generally, the more permeable the soil, the greater the influence of infiltration on model outcomes.

2.4.5 Surface roughness

Surface roughness refers to the irregularities that form the three-dimensional texture of a surface (Ruzova & Haddadi, 2025). In hydrodynamic modelling, surface roughness plays a key role in overland flow processes, as increased roughness slows runoff velocity and leads to greater surface water retention, resulting in greater flow depths (Sadeh et al., 2018). It also influences the timing and magnitude of peak discharge. Surface roughness is controlled by factors such as geology, geomorphology, and vegetation cover.

In flood modelling, surface roughness is commonly represented using Manning’s roughness coefficient, where a higher Manning’s value indicates faster water flow (MSB, 2023). For detailed and in-depth analyses, roughness should vary spatially according to land use. When assigning roughness values based on land use, the layering order of overlapping surface types is important to ensure that the correct roughness value is assigned to the surface physically present at the top. Recommended starting values range from $M = 5 \text{ m}^{1/3}/\text{s}$ for forested areas and railway surfaces to $M = 70 \text{ m}^{1/3}/\text{s}$ for paved roads, though values may need to be adjusted to reflect local conditions.

2.5 Modelling in MIKE+

MIKE+ is the latest integrated modelling software developed by the Danish Hydrological Institute (DHI) (DHI, 2025). The software is designed for the analysis and design of water distribution systems, wastewater and stormwater collection networks, and river systems (DHI, 2026). Beyond these individual system types, MIKE+ supports 2D overland flow modelling and enables fully integrated network-surface simulations, making it well suited for flood analysis and urban water management studies.

A key feature of MIKE+ is its ability to combine multiple system components within a single modelling environment (DHI, 2026). Users can activate and couple link catchments, collection system networks, river networks, and 2D overland models depending on the requirements of the analysis (DHI, 2023, 2026). Collection system

networks are modelled as 1D networks, in which flow is computed along discrete pipes and channels connecting nodes such as manholes and outlets, and can be fully coupled to the 2D surface model. However, when focusing solely on surface water dynamics under extreme rainfall, the 2D overland module in MIKE+ can be adequately applied without any further coupling.

2.5.1 MIKE+ 2D Overland Flow Model

The 2D Overland flow module in MIKE+ is designed to simulate 2D free-surface flows across land surfaces and overland water bodies (DHI, 2026). The module can be applied to a range of overland flow scenarios, including pluvial, fluvial, and coastal flooding, provided that vertical flow stratification is negligible. The hydrodynamic component of the module simulates water level variations and flow responses to various forcing functions, making it well suited for flood risk assessment and cloudburst analysis.

To set up the 2D model, the user first defines a computational domain, essentially the area over which the simulation will run (DHI, 2026). This is done in the 2D Domain editor. The domain can be represented either as a rectangular grid with uniformly spaced cells or as a flexible mesh made up of triangular and quadrangular elements of varying sizes. The rectangular grid is defined by specifying the cell size along the x- and y-directions as well as the spatial extent of the domain, which can be derived directly from the available topographical data layers. An elevation threshold can also be set, above which grid cells are excluded from the computations. Once the domain is defined, terrain elevation data are interpolated onto the grid or mesh from input files such as raster data, which forms the topographic foundation that determines how water moves across the surface.

The flow is solved numerically, and in the 2D numerical settings the user can choose between a lower-order and a higher-order numerical scheme for both time integration and space discretisation (DHI, 2026). The lower-order scheme is faster to run, while the higher-order scheme is significantly more accurate but increases computational time. The module also handles wet and dry boundaries, determining dry and flooded areas. This is done by checking the water depth in each element and classifying it as dry, partially dry, or wet using predefined depth thresholds.

Initial conditions for the model can be described in three ways, as a dry domain, with uniform water level or as varying in domain (DHI, 2026). For a dry domain, the simulation starts with no water velocity or depth across the domain. Using a uniform water level as the initial condition means that a water level value is applied to the entire domain at the beginning of the simulation. Finally, varying in domain allows water levels to be spatially distributed across the domain at the start of the simulation. This requires either an input file or a layer describing the conditions across the domain.

In 2D overland flow modelling, water flow is affected by turbulence and flow variations that occur at scales smaller than the model grid (DHI, 2026). In MIKE+, these effects are accounted for through an eddy viscosity formulation, which introduces a diffusion-like term in the momentum equations to smooth out numerical instabilities. The eddy viscosity can be specified as either uniform across the model domain, or spatially varying.

Three key physical parameters that must be defined as input to the 2D overland model are surface roughness, infiltration and rainfall (DHI, 2026). Surface roughness in the 2D model can be specified in four ways: as a uniform value, varying in domain, varying in domain and time, or varying in domain and flow dependent. The varying in domain option allows roughness values to differ spatially across the model domain. This option supports several input formats, including graphically defined roughness polygons directly in MIKE+, background layers from shape files, or a pre-defined 2D file. Concerning infiltration, there are several infiltration types available in MIKE+, ranging from no infiltration to spatially and temporally varying infiltration that accounts for the capacity of the infiltration. The varying in domain using capacity option uses a simplified infiltration model that calculates net infiltration based on specified properties of the surface zone. The infiltration input contains spatially distributed information on infiltration zone properties. Finally, rainfall is added to the model as a precipitation input. Several formats are supported, from a simple constant rainfall intensity applied uniformly across the domain, to fully spatially and temporally varying rainfall fields. For precipitation varying in domain and time, a DFS2 grid data file is required as input.

Boundary conditions can be applied along the edges of the domain, controlling how water enters or leaves the model (DHI, 2026). By default, the domain is fully closed, but other types of boundaries can be defined where needed. The boundary can be described as a prescribed discharge, a fixed water level, a local source (or sink), a discharge and water level correlation, or a free outflow condition. Free outflow is typically applied at downstream boundaries where water is assumed to leave the model domain without restriction.

3. Case Study Area

This chapter presents an overview of the case study area selected for the pluvial flood analysis. The following sections describe the geographic and demographic context, physical characteristics, subsidence conditions, and the stormwater regulations governing the area, providing the necessary background for the modelling approach presented in Sections 4.2 and 4.3.

3.1 Geographic and demographic context

The study area is located in Gothenburg, Sweden’s second-largest city by population, with 613,434 inhabitants in 2025 (SCB, 2026). Figure 3.1 displays the location of the case study area. In 2024, Gothenburg had a population density of 1352.7 inhabitants/km² (SCB, 2024). Gothenburg is a city that has experienced prominent urbanisation in recent decades and is expected to continue to grow, with the target of adding 150,000 new inhabitants between 2020 and 2035 (Kretslopp och vatten, 2020a). Situated low-lying by the sea with varied topography and poorly draining soils, Gothenburg is exposed to a range of climate-related risks, particularly flooding. Furthermore, when Gothenburg grows, land development contributes to a greater share of impervious surfaces, increasing the surface runoff and flooding risk.

The study area spans over an area in central Gothenburg of approximately 1.5x1.5 km². More specifically, the area includes Haga, Vasastaden and crosses the Rosenlund Canal to include Vallgraven. Göta Älv is the recipient that along with Rosenlundskanalen and Stora Hamnkanalen, handles the discharge from pipe networks and surface runoff (Kretslopp och vatten, 2020b). The area contains extensive infrastructure with tramways, bus paths, and heavy traffic. Furthermore, the area consists of 215 buildings, making the area highly developed (Wikby et al., 2024).

The area was selected based on previous geotechnical studies assessing time-dependent groundwater-induced subsidence and building damage in central Gothenburg, from which subsidence data could be obtained (Haaf et al., 2024; Wikby et al., 2024, 2025). Due to its geotechnical origin, the selected area does not encompass a complete natural catchment. Thus, it was extended to include the full drainage boundaries required for cloudburst modelling. This is explained further in Section 4.2.1.

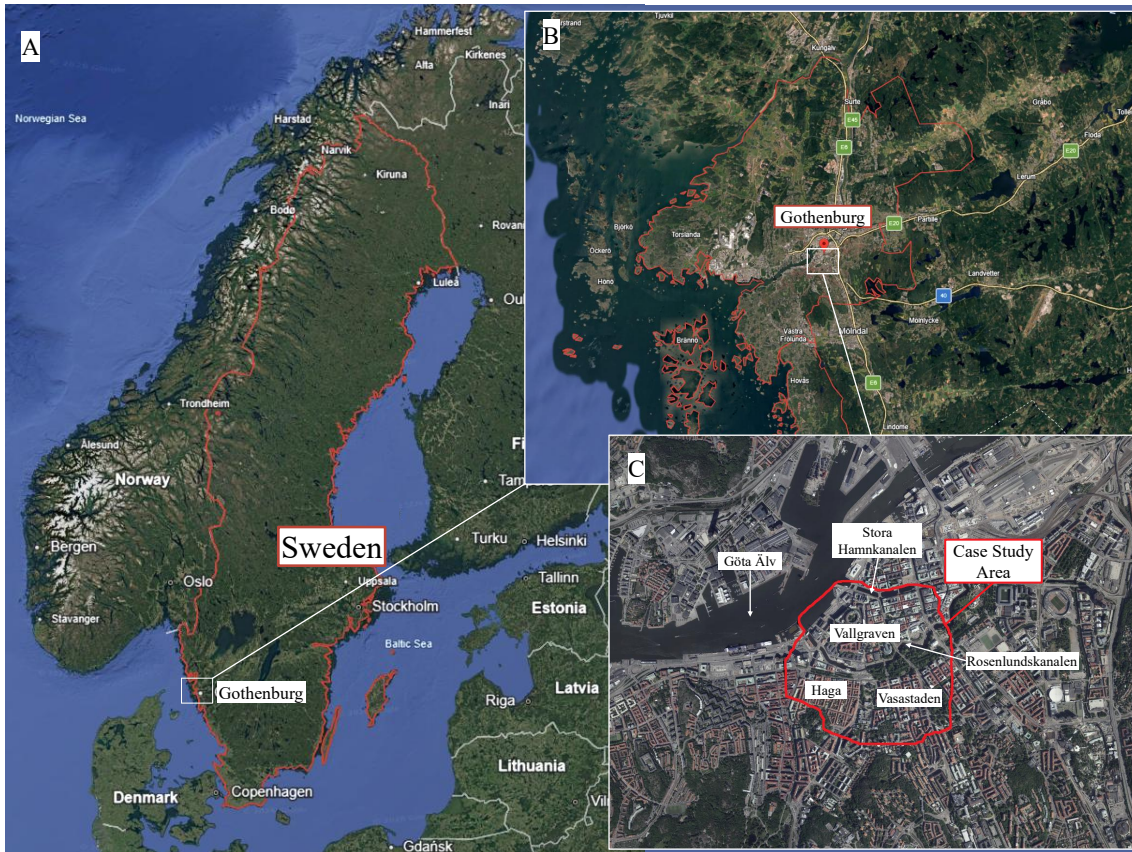


Figure 3.1: (A) Location of Sweden and Gothenburg. Annotated map from Google Earth (Google LLC, 2026). Map data ©2026 Google. (B) Location of case study area in Gothenburg. Annotated map from Google Earth (Google LLC, 2026). Map data ©2026 Google. (C) Case study area and location of Göta Älv, Stora Hamnkanalen, Rosenlundskanalen, Haga, Vallgraven and Vasastaden. Annotated map from Scalgo (n.d.a).

3.2 Physical characteristics

This section describes the physical characteristics of the case study area, including its topography, land cover, and soil conditions.

The topography of the case study area is illustrated in Figure 3.2, where contour lines are drawn at 5 m and 1 m elevation intervals, respectively. The terrain varies substantially across the study area, comprising both elevated and low-lying areas. The terrain slopes steeply from a higher area in the south-east, reaching approximately 50 m above sea level, down towards the canal. North of Rosenlundskanalen, the elevation increases again before descending towards a low-lying area situated near Göta älv. These elevation differences influence surface runoff patterns and may affect the spatial distribution of flooding within the study area (Chindo, 2025).

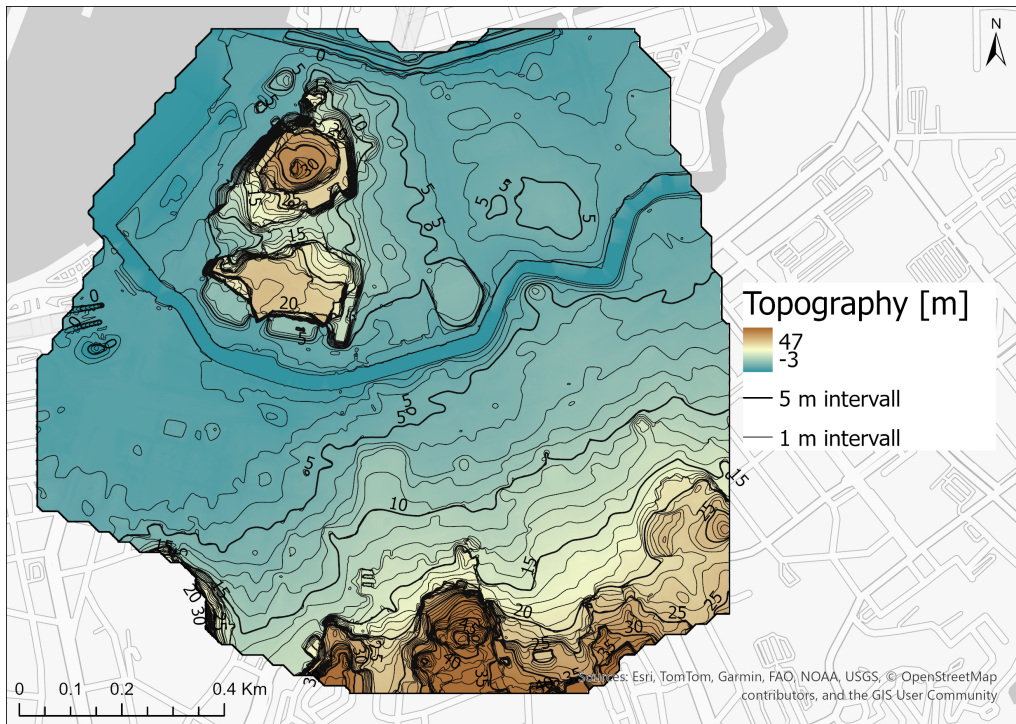


Figure 3.2: Topography map of the case study area retrieved via Scalgo (n.d.a). @Lantmäteriet. The elevation refers to meters above sea level and the contour lines represent 5 m and 1 m change in elevation. Map produced by the authors.

The land cover of the case study area is dominated by impervious surfaces, such as buildings and paved roads. See Figure 3.3. This reflects the highly urbanised character of the area and influences surface runoff processed by limiting infiltration and increasing the proportion of direct surface flow.

Regarding the geological conditions, soil characterisation data presented in Figure 3.4 indicate that the majority of the study area is underlain by postglacial clay. Along the banks of the Göta älv, the ground primarily consist of anthropogenic fill material. These deposits are related to historical land reclamation and quay expansion, where fill consisting of gravel, sand and silt mixed with demolition debris and remnants of older foundation structures has been placed to extend the riverfront (Göteborgs Stad, 2012). The extensive filling within the area has caused consolidation of the underlying clay deposits, resulting in long-term subsidence estimated to approximately 1-1.5 m since the late nineteenth century.

A comparison between Figure 3.2 and Figure 3.4 shows that the highest elevation within the study area generally coincide with locations where bedrock is exposed. Further geological characterisation is discussed in Section 3.3.

3. Case Study Area

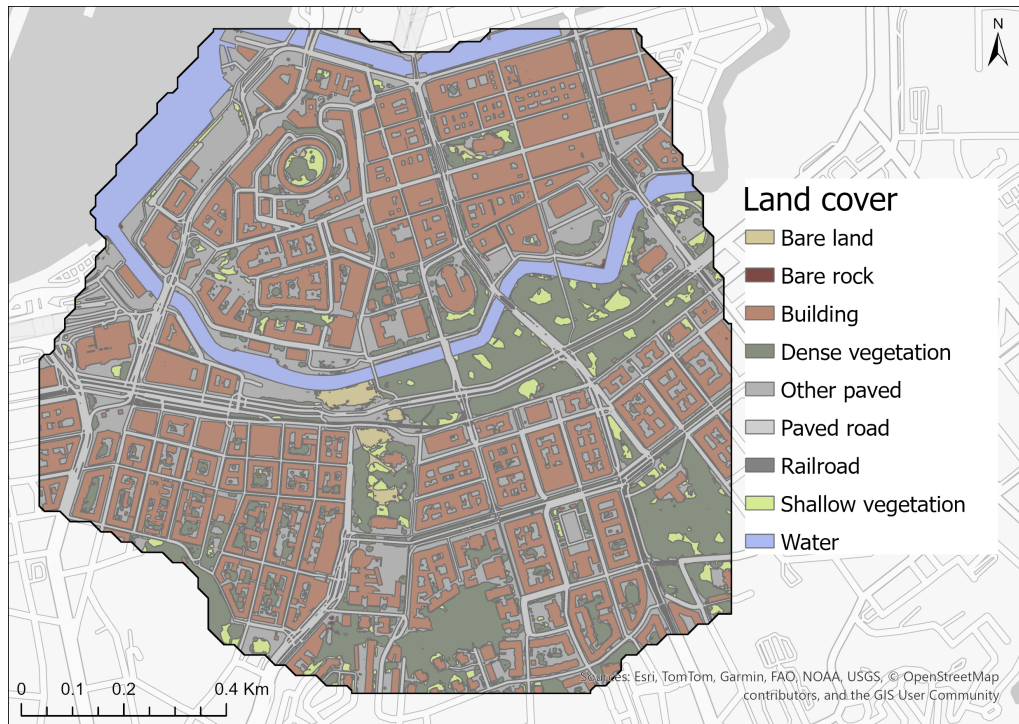


Figure 3.3: Land cover of the case study area retrieved via Scalgo (n.d.a). @Lantmäteriet. Map produced by the authors.

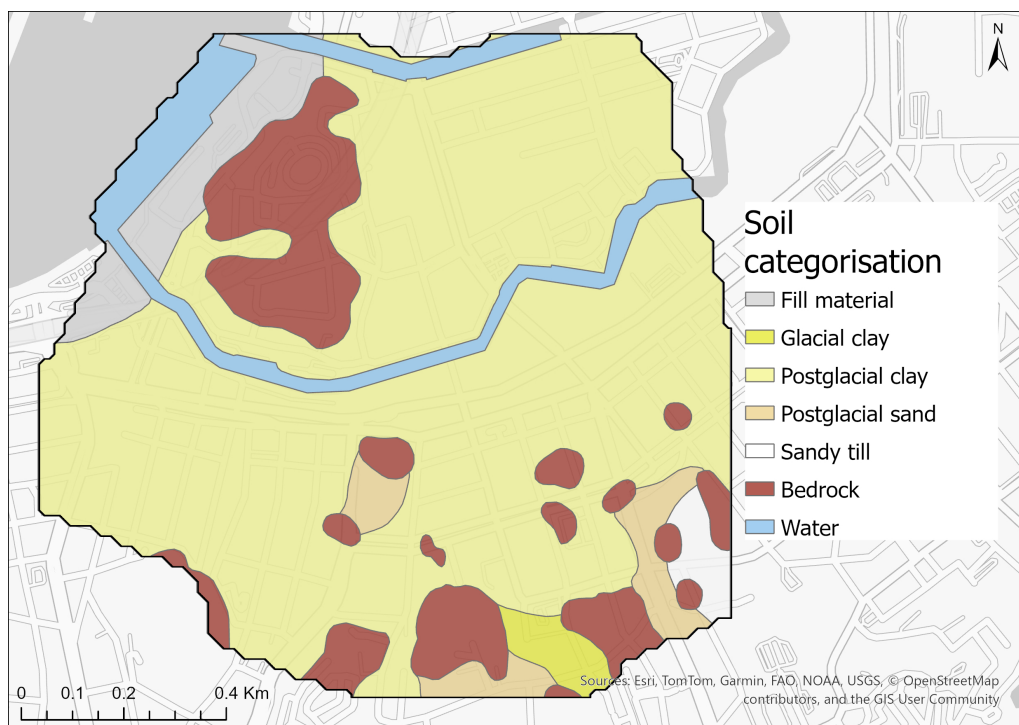


Figure 3.4: Geological soil categorisation over the case study area. Adapted from data by Geological Survey of Sweden (2026a) retrieved via Scalgo. Map produced by the authors.

Soil depth to bedrock within the study area is presented in Figure 3.5. In certain parts of the area, the soil depth reach up to 70 m, while in other parts there is exposed bedrock. Large parts of the area exhibit soil depths exceeding 10 m, coinciding with areas of postglacial clay or fill. Where postglacial clay is present, soil depth is assumed to represent clay depth based on observations from Geological Survey of Sweden (2024). A comparison between Figure 3.5 and Figure 3.2 further shows that the greatest soil depths consistently coincide with the lowest-lying terrain.

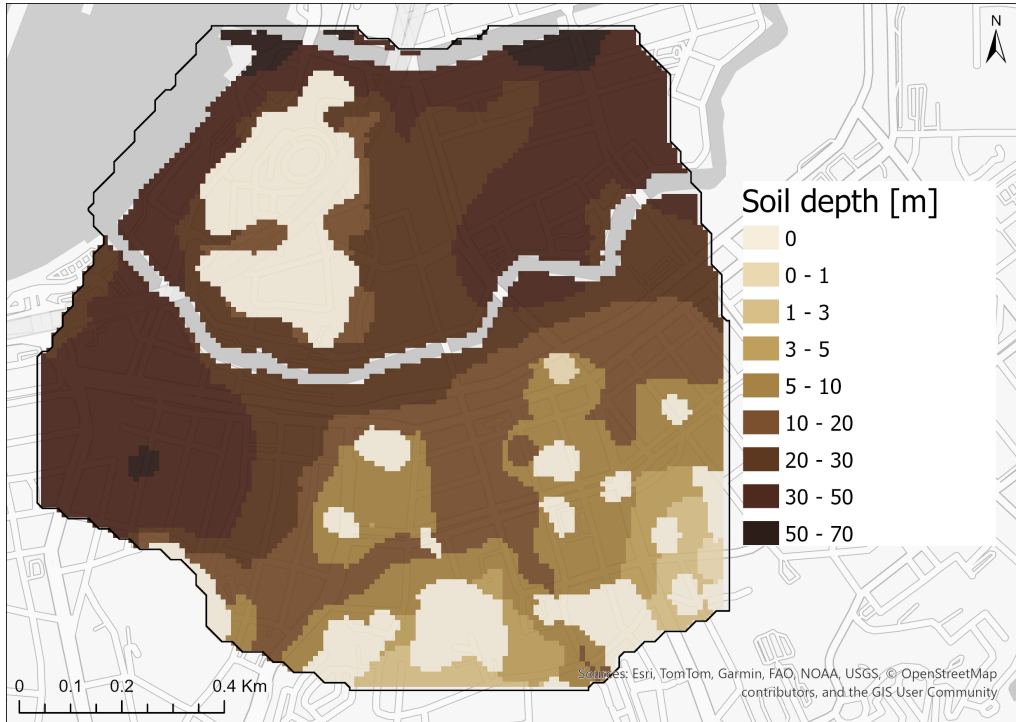


Figure 3.5: Soil depth [m] to bedrock within the case study area. Adapted from data by Geological Survey of Sweden Geological Survey of Sweden (2023). Map produced by the authors.

3.3 Subsidence conditions

The case study area in Gothenburg is subject to ongoing subsidence driven by a combination of natural soil conditions and the effects of urban development (Wikby et al., 2024). The upper clay layer of the study area has been substantially modified by urban development activities, including the construction of foundations and buried infrastructure. These activities combined with natural conditions have resulted in persistent long-term creep-related subsidence on the order of 2-5 mm per year.

Ground surface deformation data can be obtained from the Swedish Geotechnical Institute's open InSAR viewer (Swedish Geotechnical Institute, 2026a), which provides satellite-based measurements of ground movement across Sweden (Swedish Geotechnical Institute, 2026b). Figure 3.6 shows the spatial distribution of measured ground movement [mm/year] within the case study area. The data covers the period 2015-2021. Figure 3.7 shows areas of negative displacement, indicative of ongoing subsidence, and is used as a basis for identifying areas potentially suscep-

ible to subsidence-related impacts on pluvial flooding. The figure shows that the highest rates of subsidence (larger negative ground movements) are concentrated in the western and north-eastern parts of the case study area. Areas without data points generally reflect low measurement coherence, for instance due to vegetation cover, rather than an absence of ground movement (Swedish Geotechnical Institute, 2026b).

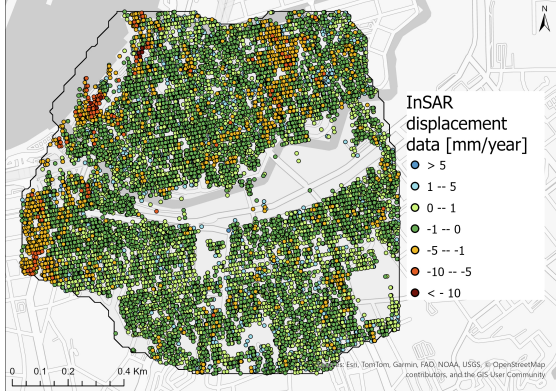


Figure 3.6: Measured ground movement within the case study area based on InSAR data from (Swedish Geotechnical Institute, 2026a). Data covers the period 2015-2021. Map produced by the authors.

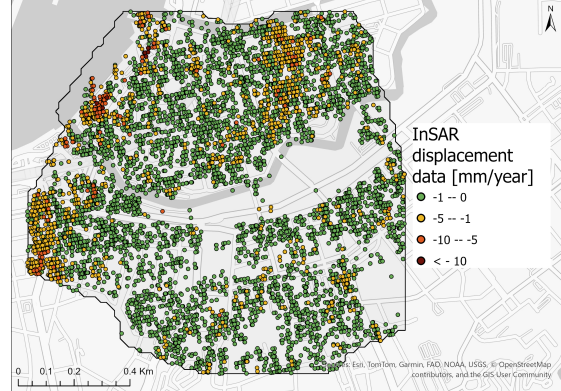


Figure 3.7: Measured negative displacement within the case study area based on InSAR data from (Swedish Geotechnical Institute, 2026a). Data covers the period 2015-2021. Map produced by the authors.

The predicted subsidence, 100 years from now, used in the MIKE+ model was calculated by Wikby et al. (2024) at Chalmers Technical University. The following methodology was used to estimate subsidence. A geostatistical stratigraphy model based on borehole data was first developed and used to construct and calibrate a MODFLOW groundwater model. Subsequently, a hydro-mechanically coupled finite-element model was established in PLAXIS 2D, in which the Creep-SCLAY1S constitutive model was applied to represent clay creep, anisotropy, and debonding. Model parameters were calibrated using laboratory oedometer and triaxial tests, along with subsidence measurements from a bellow hose. Finally, a statistical meta-model trained on several two-dimensional cross sections was employed to upscale the results and predict subsidence across the entire study area. Figure 3.8 shows the results of subsidence in the area 100 years from now. The result showed varying subsidence in the area, between approximately 0.5 and 32 cm, likely due to the soil stratigraphy that moves from exposed bedrock to clay prone to subsidence.

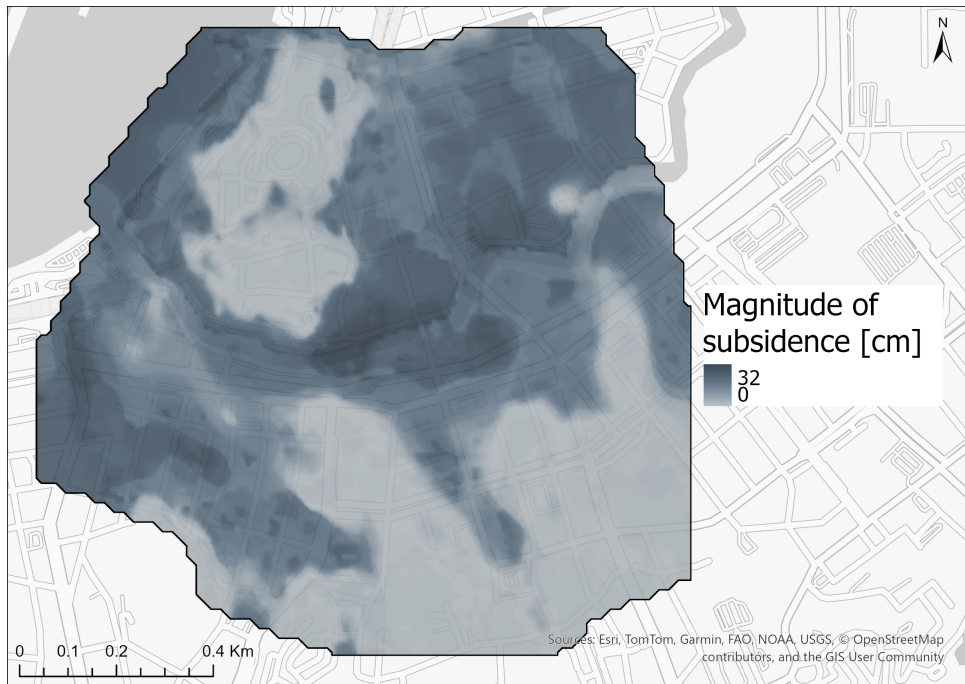


Figure 3.8: Spatial distribution and magnitude [cm] of subsidence within the case study area based on results from Pierre Wikby’s meta-model (Wikby et al., 2024). Map produced by the authors.

3.4 Stormwater regulations

Göteborg is one of the most rain-intensive cities in Sweden, with a mean of 917 mm/year between the years 1991 and 2020 (Göteborgs Stad, n.d.). Based on historical monthly precipitation data, the City of Göteborg has designated July and August as its cloudburst season. Over the past three decades, four heavy rainfall events distinct from other types of rainfall have been recorded. These events are characterized by reduced functionality in transport infrastructure and by conventional stormwater infrastructure being unable to manage the associated water volumes.

The City of Göteborg has created a policy document guiding how Göteborg should plan and adapt to flood risks within its overall city planning framework (Göteborgs Stad, 2019). New development must be protected against flooding through planning measures. Construction should either be situated at a safe elevation or incorporate appropriate technical safety measures. The detailed plan map must indicate the minimum allowable elevation to reduce the risk of damage. While previous planning focused on protecting critical societal facilities, such as hospitals and heavy infrastructure, from flooding, the latest supplement extends planning levels to other societal assets and valuable objects (Göteborgs Stad, 2019). For extreme rainfall events with a 100-year returning period, no more than 20 cm of water is permitted on high-priority roads, routes, and evacuation paths. For buildings, a clearing distance of 20 cm applies between the surrounding ground level and the finished floor or any essential part necessary for the building’s function. This level is increased to 50 cm when the building is of special societal necessity. While these

planning levels are not directly enshrined in law, they carry significant practical weight. As discussed in Section 2.1.2, the Planning and Building Act requires that detailed development plans be assessed from a climate adaptation perspective, and the County Administrative Board may revoke plans that fail to adequately address cloudburst risks (MSB, 2022; Salomonsson et al., 2017). In practice, this means that detailed plans in Gothenburg that do not account for the planning levels set out in the Gothenburg policy document are unlikely to be approved. The recommended planning levels thus become indirectly binding, not through explicit legislation, but through the regulatory framework that governs the planning process.

However, these planning requirements apply primarily to new development. Many parts of Gothenburg have been urbanised for many years, for example, Haga, whose oldest existing building today dates from the 1780s (HSB, n.d.). As a result, many such areas lack infrastructure designed for modern stormwater management. To enable long-term cloudburst management in the built urban environment, the City of Gothenburg released 15 structural plans covering the entire city in 2020 (Kretslopp och vatten, 2021b). The structural plans were developed using hydrodynamic modelling, where surface runoff was simulated using MIKE 21 FM coupled with an existing pipe network model. Based on the modelling, the structural plans focus on identifying facilities aimed at reducing flood risks at a broader scale. Primary emphasis is placed on societal risks, including protecting critical infrastructure and ensuring accessibility on prioritized road networks. The plans comprise action chains, cloudburst pathways, cloudburst areas, and flow control structures. The proposed facilities are classified into three priority levels (A-C), based on the type of activity of infrastructure they aim to protect: Priority A covers facilities protecting healthcare and emergency services, Priority B covers schools, municipal governance, communication infrastructure, and major roads, while Priority C encompasses all remaining facilities. These plans are intended to be applied in early planning stages and to inform decision-making in detailed development planning. It is further intended that the principles and proposed facilities be incorporated into the city's comprehensive planning. At this level, land use recommendations can be visualised municipally, enabling the designation of areas and objects for specific interventions, such as construction, preservation, or demolition, to ensure long-term sustainable cloudburst management.

4. Methodology

The methodology chapter presents the methods used to address the objectives of this master's thesis. To evaluate how subsidence in Gothenburg influence urban pluvial flooding a literature review, pluvial flood modelling, and simplified risk assessment was conducted.

4.1 Literature review

The master thesis started with a literature review aimed at establishing a theoretical and methodological foundation for the study, as well as identifying existing knowledge gaps that the present research seeks to address. The review focused on subsidence processes, pluvial flood modelling, and previous studies analysing the impact of subsidence on urban flooding. Scientific publications were retrieved from the databases Scopus and Web of Science.

The search strategy was based on the combinations ("Ground subsidence" AND "hydrodynamic models" AND "flooding") and ("Settlement subsidence" AND "hydrodynamic modelling" AND "urban flooding"). The initial search resulted in a limited number of highly relevant studies, of which two were selected for further investigation. These papers were subsequently used to expand the search by forward snowballing, enabling the identification of more recent studies within the field.

To ensure scientific quality and relevance of previous studies investigated, only peer-reviewed journal articles published within the last ten years were included. The review was limited to publications written in English and primary sources were prioritised to ensure that the analysis was based on original research contributions. In total, five peer-reviewed articles presenting research closely aligned with the objectives of the present study were ultimately selected and included in the review.

4.2 Preparation of input data for MIKE+ analysis

In order to construct a 2D overland model with no couplings in MIKE+, extensive data processing was performed to prepare all input datasets. This preprocessing ensured that all inputs shared a common coordinate reference system, spatial extent, and resolution, which is essential for producing accurate simulations. All spatial data were projected in SWEREF 99 12 00 and referenced to RH2000, ensuring that raster and vector layers were correctly aligned and fully compatible with hydrodynamic modelling in MIKE+. Furthermore, all raster datasets were standardised to a resolution of 1 x 1 m and adjusted to cover exactly the same spatial extent as the catchment area. The 1 x 1 m resolution was chosen to capture detailed topographic and spatial variations within the catchment, providing sufficient granularity to represent urban features such as streets, buildings, and small-scale terrain variations that are critical for accurate overland flow simulations (MSB, 2023).

The following sections describe the main datasets and parameters used in the model. Each dataset was processed according to its specific purpose and subsequently converted into MIKE+ compatible formats in MIKE Zero. This enabled seamless integration into the model and ensured consistency across all inputs.

4.2.1 Defining the hydrodynamic model area

Prior to flood modelling, the study area was delineated to encompass the full drainage boundaries required for hydrodynamic simulation. Since the case study area does not constitute a complete natural catchment, it was extended to account for upstream runoff contributions. This was achieved through an analysis in Scalgo (n.d.a) of major depression-free flow areas connected to the case study area. Five major catchment areas were identified: four connected to Rosenlundskanalen, which flows through the case study area, and one connected to a flow path that passes through the area. The defined hydrodynamic model area, the case study area and the model domain in MIKE+ are shown in Figure 4.1. The defined hydrodynamic model area covers just under 8 km².

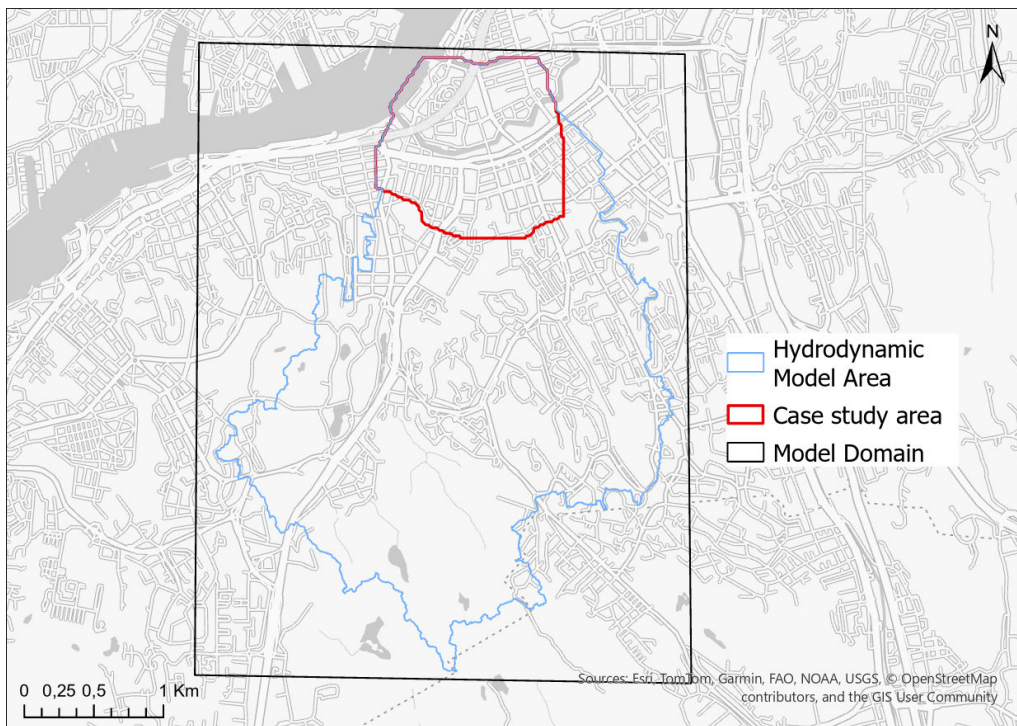


Figure 4.1: Overview of the defined hydrodynamic model area outlined in blue, the case study area outlined in red, and the model domain in MIKE+ outlined in black.

4.2.2 Digital elevation model

To enable a comparative scenario analysis of the impacts of subsidence on pluvial flood modelling, two digital elevation models (DEMs) were developed: one representing current topographic conditions and one representing the topographic conditions 100 years from now, incorporating the accumulated subsidence. By comparing simulations based on these two DEMs, the effect of subsidence on flood extent and depth can be isolated. The DEM representing current conditions consisted solely of the original elevation data "Terrain/Skog" from Scalgo (n.d.a), collected on 17 December 2025 using airborne LiDAR at a spatial resolution of 1 x 1 m.

To account for subsidence, results from the meta-model developed by Wikby et

al. (2024), as described in Section 3.3, were used to generate a raster representing the spatial distribution and magnitude of projected subsidence within the case study area. The subsidence raster had a spatial resolution of 5 x 5 m and represented the projected cumulative subsidence after 100 years.

The subsidence-adjusted DEM was produced by subtracting the subsidence raster from the baseline DEM in QGIS using the raster calculator. This effectively lowered the ground surface elevation in accordance with the projected subsidence. As the two rasters differed in spatial resolution, each 5 x 5 m subsidence cell value was applied uniformly to all underlying 1 x 1 m DEM cells, meaning that subsidence was assumed to be spatially constant within each 5 x 5 m grid cell. This represents a simplification, as subsidence may vary within a cell. However, the approach was adopted due to the resolution of the available subsidence dataset, and while it introduces some uncertainty in local elevation changes, it allows the higher-resolution DEM to be adjusted using the best available data.

Both DEMs were subsequently processed in FME Workbench to improve the representation of buildings in the pluvial flood simulations. Since buildings act as physical barriers to surface water flow, their presence must be reflected in the elevation model. A rasterised building footprint dataset was therefore overlaid onto both DEMs, and cells corresponding to building footprints were assigned an elevation of 2 m above the local ground level, in accordance with recommendations from MSB (2023). The resulting DEMs were then used as topographic input to the subsequent flood simulations conducted in MIKE+ (DHI, 2026).

4.2.3 Precipitation data

A synthetic design storm of the Chicago Design Storm (CDS) type was used as precipitation data. The rainfall statistics used to construct the CDS rain are based on the regional precipitation frequency analysis presented by Olsson et al. (2017b), and apply to region SV (south-west), which constitutes the region within which the case study area is located and represents the area with the highest rainfall intensities in Sweden (Olsson et al., 2017a).

To compute rainfall volumes for a given duration and return period, the nested power model described in Olsson et al. (2017a) and presented in Equations 4.1 to 4.3, was applied:

$$R = M(V) \cdot k(T) \cdot V^{p(T)} \quad (4.1)$$

where

- R is the accumulated rainfall volume [mm],
- V is the duration [minutes],
- T is the return period [years],
- $M(V)$ is a scaling factor that compensates for the fixed 15-minute measurement intervals of SMHI's automatic stations [-],
- $k(T)$ and $p(T)$ are parameters that depend on the return period [-].

The parameters $k(T)$ and $p(T)$ are expressed as power functions of the return period with input parameters from Table 4.1:

$$k(T) = a_1 \cdot T^{a_2} + a_3 \quad (4.2)$$

$$p(T) = b_1 \cdot T^{b_2} + b_3 \quad (4.3)$$

Table 4.1: Design parameters [-] used to construct the CDS rainfall event for a 100-year return period (Olsson et al., 2017a).

Parameter	Value
a_1	3.113
a_2	0.33079
a_3	-0.12611
b_1	0.43612
b_2	-0.045249
b_3	-0.079367

Additional parameters used to construct the CDS rainfall event are presented in Table 4.2.

Table 4.2: Design parameters for the CDS rainfall event.

Parameter	Value
Return period, T	100 years
Total duration, V	360 minutes
Skewness factor, r	0.37
Event start time	2026-07-01 15:00:00
Time of maximum intensity	2026-07-01 17:22:39

The skewness factor presented in Table 4.2 determines the timing of the rainfall peak within the event (Svenskt Vatten, 2011). A skewness value of 0.37 indicates that the intensity maximum occurs before the midpoint of the storm, at 37 % of the total duration from the start. Using this skewness factor together with the event start time, the time of maximum intensity was calculated. Subsequently, the rainfall intensity per time step [mm/h] was determined following the guidelines presented by Svenskt Vatten (2011).

The calculated rainfall intensities were then multiplied by a climate factor of 1.4 to account for projected increases in precipitation due to climate change (MSB, 2023). As described in Section 2.4.2, the appropriate climate factor depends on the planning time horizon and chosen emission scenario. Since this study evaluates flood conditions approximately 100 years into the future, extending beyond the 2071-2100 period for which climate factors are currently recommended, the upper end of the recommended range was applied. A climate factor of 1.4 corresponds to the high-emission scenario (RCP8.5) for the end of the century (MSB, 2023), representing a conservative and precautionary approach. Finally, four hours with zero precipitation were appended to the constructed rainfall to allow the hydrodynamic model to continue running.

The precipitation data were converted to a dfs0 file using the time series tool in MIKE Zero by creating a Blank time series. A non-equidistant calendar axis was

chosen, with precipitation rate as the variable type and mm/h as the unit. The start time was set to 2026-07-01 15:00 and the number of time steps was set to 49. The calculated time steps and corresponding precipitation rates were then inserted to create the final CDS rainfall series, as illustrated as the black line in Figure 4.2.

4.2.4 Drainage network deduction

To account for the capacity of the sewer and stormwater system within the case study area, a deduction was applied to the precipitation rate. The sewer system is assumed to be capable of managing a volume equivalent to a 10-year return period event (Kretslopp och vatten, 2021b). The reduction therefore corresponds to the rainfall volume of a 10-year return period event with a duration of 6 hours, which yields a total volume of 41.6 mm according to the Dahlström rainfall distribution. This translates to a constant reduction of 6.93 mm/h applied uniformly over the storm duration.

The final CDS rainfall used in the modelling is presented as a hyetograph in Figure 4.2, with rainfall intensities for each time-step tabulated in Appendix 1. The deduction was distributed spatially based on land cover classification, as the sewer system is assumed to collect runoff exclusively from impervious surfaces, in accordance with MSB (2023). This results in a spatially differentiated rainfall, in which the full 100-year return period rainfall (black line, Figure 4.2) is applied to pervious surfaces, while a reduced rainfall accounting for sewer system capacity (blue line, Figure 4.2) is applied to impervious surfaces.

4.2.5 Manning

To account for surface roughness in the model, a manning file was created for the entire catchment area. Land cover data, based on data from Lantmäteriet acquired in 2025, was exported from Scalgo (n.d.a) and imported into QGIS. Each land cover class were assigned a Manning's M according to MSB (2023), see Table 4.3.

Table 4.3: Land cover class and Manning's M values [$\text{m}^{1/3}/\text{s}$] from MSB (2023).

Land cover class	Manning's M
Unpaved road	40
Bare land	20
Shallow vegetation	20
Dense vegetation	5
Field	20
Bare rock	30
Railroad	5
Building	50
Paved road	70
Other paved	40
Water	50

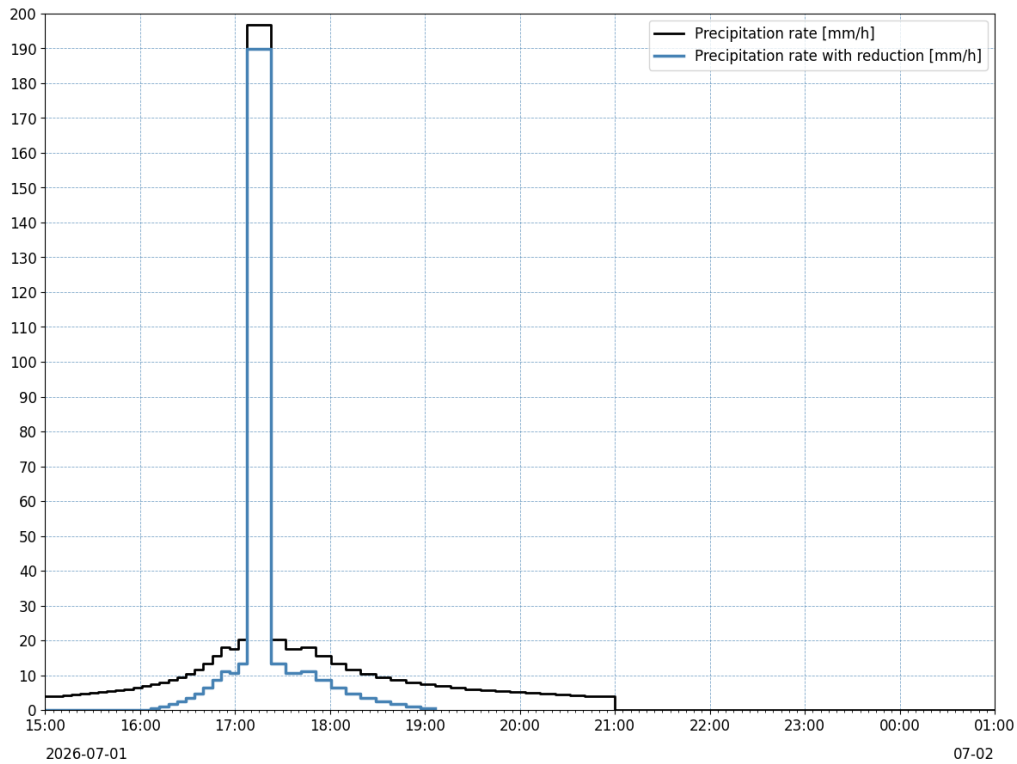


Figure 4.2: Hyetograph of the CDS rainfall event used as input to the hydrodynamic model, illustrating the temporal distribution of precipitation intensity [mm/h] for two scenarios: a rainfall event with a 100-year return period (black line) and the same rainfall with a reduction of a rain event with a 10-year return period to include the drainage network deduction (blue line).

4.2.6 Infiltration module

An infiltration module was created for the catchment area in QGIS. The infiltration module consists of five parameters: infiltration capacity [mm/h], porosity [-], leak rate [mm/h], saturation degree [-], and thickness [m]. The module was created based on the basic soil layer sequence from Geological Survey of Sweden (2026a), exported from Scalgo (n.d.a). Impervious surfaces were subtracted from the infiltration module based on land cover categorisation. Areas classified as paved, other paved, or buildings were therefore not included in the infiltration module as these do not have infiltration capacity. Each type of soil was assigned values for each infiltration parameter, see Table 4.4. Values for infiltration and leak rate were collected from Kretslopp och vatten (2021b), while values for saturation degree and porosity were collected from MSB (2023). For thickness, values from both Kretslopp och vatten (2021b) and Stockholms stad (2025) were used as references.

4.2.7 Receiving water bodies in the study area

For the water bodies located in the southern part of the hydrodynamic model area, whose entire catchment is included within the study area, the infiltration parameters shown in Table 4.4 were applied. Water levels were set according to elevation data retrieved from (Scalgo, n.d.a) and could rise freely during the simulation depending

Table 4.4: Soil parameters used in the infiltration module (Kretslopp och vatten, 2021b; MSB, 2023; Stockholms stad, 2025).

Soil type	Infiltration [mm/h]	Saturation degree [-]	Porosity [-]	Leakage rate [mm/h]	Thickness [m]
Peat bog	18	0.20	0.80	1.8	0.3
Postglacial silt	3.6	0.30	0.30	0.36	0.3
Fen peat	18	0.20	0.80	1.8	0.3
Postglacial clay	3.6	0.35	0.45	0.36	0.3
Sandy till	36	0.20	0.15	3.6	0.3
Water	0	1	0	0	0
Postglacial fine sand	180	0.10	0.25	36	0.3
Glacial clay	3.6	0.35	0.45	0.36	0.3
Bedrock	36	0.10	0.05	0.036	0.1
Weathered soil, sand–gravel	180	0.15	0.25	36	0.3
Postglacial sand	180	0.10	0.25	36	0.3
Fill material	36	0.20	0.15	3.6	0.3
Wave-washed sediment, gravel	180	0.15	0.30	36	0.3

on the inflow to the water bodies.

The case study area covers a small part of Göta Älv, Rosenlundskanalen, and Stora Hamnkanalen. For these water surfaces, adjustments were made in the infiltration module to prevent unrealistic accumulation of water levels. Flood-prone areas were identified using the Scalgo Live flash flood mapping tool (Scalgo, n.d.b), where no significant risk was observed around the aforementioned waterways. Since all three waterways are receiving water bodies whose full catchments are not represented in the model, the infiltration module was adjusted to maintain a constant water level by assigning an effectively unlimited infiltration capacity and leakage rate, allowing the system to handle all incoming water. This modelling correction prevents artificial water build-up and avoids the need to define separate internal boundary conditions in the flood models. Normally, boundary conditions are applied along the edges of a catchment area, but in this case the waterways are within the model domain, making it difficult to apply separate boundaries. These adjustments align with the methodology of Kretslopp och vatten (2021b) and Stockholms stad (2025).

Additionally, a fixed ground elevation of +0.85 m RH2000 was assigned to Göta Älv, Rosenlundskanalen, and Stora Hamnkanalen, corresponding to the projected future water level of Göta Älv (Kretslopp och vatten, 2021b). This was done in the DEMs in MIKE Zero, creating selections of the water bodies and assigning height values. Conceptually, these waterways were treated as if they were a highly permeable ground surface with virtually unlimited infiltration capacity, meaning that their water levels remain effectively constant even during extreme rainfall events. This approach was a deliberate simplification, as the model does not include a detailed channel or flow description. Instead, infiltration parameters control the water levels, preventing artificial fluctuations and ensuring numerical stability, with infiltration capacity and leakage rate assigned unrealistically high values to reflect this.

The corrected infiltration parameters can be seen in Table 4.5. The saturation degree, porosity, and thickness were also modified with assumed values to represent

water bodies with effectively unlimited infiltration capacity. However, infiltration capacity and leakage rate have the largest effect on the infiltration module.

Table 4.5: Adjusted infiltration parameters for receiving water bodies.

Water body	Infiltration [mm/h]	Saturation degree [-]	Porosity [-]	Leakage rate [mm/h]	Thickness [m]
Göta Älv	15000	0.001	0.5	15000	1
Rosenlundskanalen	15000	0.001	0.5	15000	1
Stora Hamnkanalen	15000	0.001	0.5	15000	1

4.3 Model setup

The hydrodynamic model was configured in MIKE+ based on the input data described in Section 4.2. This section describes how the computational domain was defined, how the model was technically configured, and what boundary conditions were applied.

4.3.1 Model domain and flow paths

The computational grid (model domain) in MIKE+ is defined in a rectangular x–y coordinate system, whereas the hydrodynamic model area has a polygonal extent, as shown in Figure 4.1. To exclude areas outside the hydrodynamic model area within the model domain, these cells were assigned an artificially high terrain elevation of 250 m. Selected areas were subsequently lowered from these elevated cells to create hydraulically active pathways. Three areas were defined: the first two represent the outlet connections from Rosenlundskanalen and Stora Hamnkanalen to Göta Älv, respectively, and the third represents a major flow path conveying water out of the research area to a discharge point located slightly south of the Göta Älv outlets. The first two outlet areas were assigned elevations corresponding to the projected future water level of Göta Älv (+0.85 m RH2000), while the third area was given an elevation slightly lower than the surrounding terrain to establish a controlled and hydraulically continuous flow path. This approach created clear flow paths, allowing water to move naturally across the model and exit the study area.

To ensure proper functioning within the 2D overland model, valid infiltration parameters and Manning’s roughness coefficients were assigned to the modified cells. The infiltration parameters were defined according to Table 4.5, and a Manning number $M = 70$ was applied to represent surface roughness.

4.3.2 Model configuration

The model was configured as a 2D overland flow model using the hydrodynamic (HD) module in MIKE+, with a rectangular domain and a uniform mesh resolution of 1×1 m. Buildings are represented as elevated terrain and no coupling to a 1D pipe network or a river network model was included, as described in the preceding sections. The drying and wetting depths were set to 2 and 3 mm respectively, based on values commonly applied in cloudburst modelling practice in Gothenburg, as recommended by the supervising engineers. The low-order numerical solution

scheme was selected to reduce computational time. A dry initial condition was applied, assuming no antecedent moisture or accumulated surface water prior to the cloudburst event. The simulation duration was set to 10 hours, exceeding the 6-hour rainfall event to allow surface water to drain through the model domain following the cessation of rainfall. The remaining technical parameters applied in the model are summarised in Table 4.6 and default values recommended in the MIKE+ documentation were adopted where no study-specific reasoning motivated a different choice. The simulated event corresponds to the 1st of July 2026, with a simulation duration of 10 hours starting at 15:00. The model was configured to output water depth, flux, and velocity across the model domain, including the maximum values of each, as these parameters are most relevant for assessing flood impacts.

Table 4.6: Model technical parameters.

Parameter	Value
Drying depth	2 mm
Wetting depth	3 mm
HD numerical solution	Low order
Fluid properties	Clear water
Eddy viscosity	0.002 m ² /s (Uniform)
Initial condition	Dry domain
Simulation duration	10 h
Time step	Min: 0.01 s, Max: 10 s

4.3.3 Boundary conditions

Open boundary conditions with free flow were applied at three predefined outlet locations along the edges of the model domain. These boundaries allow water to leave the computational domain and prevent artificial accumulation at the model edges.

Two of the outlets represent hydraulic connections to Göta älv via Rosenlundskanalen and Stora Hamnkanalen. At these locations, the ground level in the terrain model was set to +0.85 m (RH2000), corresponding to a projected future water level in Göta älv. The third outlet represents a major flow path conveying water west out of the model domain; here, the ground level was set slightly below the surrounding terrain to ensure a continuous gradient towards the boundary.

Although open boundary conditions were applied, high infiltration rates were additionally prescribed at the boundary cells to prevent any residual water accumulation. This is described in detail in Section 4.2.7. Drainage at the outlets was thus governed by the combined effect of the prescribed terrain levels, which provide topographic control over the flow direction, and the open boundary conditions, which permit unrestricted discharge from the domain.

No dynamic coupling to a 1D river or channel model was included. The downstream water level at the canal outlets was therefore held constant at +0.85 m (RH2000) throughout the simulation, and no backwater effects from the receiving

waters were accounted for.

4.4 Assessment of model reliability

To assess the performance of the model constructed within this thesis, the water volume within the model domain was analysed in MIKE Zero. The evaluation was conducted by comparing the results of the developed model with current ground conditions, hereafter referred to as the Thesis model, with two combined pluvial flood models produced by the City of Gothenburg, hereafter referred to as the Reference model. Since the Thesis model covers parts of two separate reference model domains, three spatial selections were defined to facilitate comparison at peak water depth. The total water volume within each selection was estimated by multiplying the mean maximum water depth by the number of grid points in the corresponding area. To ensure a consistent comparison, the results were normalised with respect to their respective climate factors. Furthermore, since the Reference model applies a grid resolution of 4 x 4 m compared to 1 x 1 m in the Thesis model, the Reference model results were multiplied by a factor of 16 to account for the difference in cell area.

As shown in Table 4.7, the Thesis model yields a higher total water volume for than the Reference model across all three selections. However, the results are of the same order of magnitude, and the discrepancies can be attributed to several methodological differences. The Thesis model accounts for sewer capacity through a simplified reduction corresponding to a 10-year return period, whereas the Reference model employs a coupled 1D model for the sewer system (Kretslopp och vatten, 2021b). Furthermore, the Reference model has been corrected for building archways and drive-through passages, ensuring that ground level is accurately represented at these locations (Kretslopp och vatten, 2021b). This correction has not been applied in the Thesis model, which may result in water becoming artificially trapped within enclosed courtyards, contributing to the higher simulated water volumes.

Table 4.7: Comparison of total water volume [m^2] between the Thesis model and the Reference model for each spatial selection.

	Thesis model	Reference model
Selection 1	17280	14989
Selection 2	6238	4777
Selection 3	8112	7357

In addition, another assessment of model reliability was conducted by examining the volume balance summary generated from MIKE+ at the end of the summary. According to DHI (2026) deviations in the continuity balance may be caused by the numerical scheme and should remain as low as possible. The thesis model had a continuity balance of 2.23 m^3 , corresponding to a relative deficit of 0.00085 %, which is considered negligible and indicates a reliable model setup.

4.5 Simplified risk assessment

To provide an early stage assessment of where subsidence may influence pluvial flood outcomes in the case study area, a simplified risk assessment was conducted

by overlaying spatial data from multiple open sources (Geological Survey of Sweden, 2023, 2024, 2026a; Scalgo, n.d.a; Swedish Geotechnical Institute, 2026a). The analysis was designed to reflect an approach applicable in early planning stages, such as during the scoping of a new development, where a full hydrodynamic modelling assessment may not yet be warranted.

Ground movement data (Figure 3.6) was obtained from the Swedish Geotechnical Institute's InSAR viewer (Swedish Geotechnical Institute, 2026a), providing measured surface displacement across the study area for the period 2015–2021. Areas exhibiting negative line-of-sight displacement, indicative of ongoing subsidence, were identified and mapped. This data was subsequently overlaid with topographic data (Scalgo, n.d.a) (Figure 3.2), soil categorisation data (Geological Survey of Sweden, 2026a) (Figure 3.4), and soil depth data (Geological Survey of Sweden, 2023) (Figure 3.5) in ArcGIS to assess correlating factors that could contribute to an increased flood risk.

Finally, the flood results from the MIKE+ analysis when not accounting for subsidence were compared with the identified subsidence zones to assess whether areas already exposed to flood risk are also subject to ongoing ground movement, and whether subsidence is likely to compound existing risks or give rise to new ones. The results of the simplified risk assessment are subsequently evaluated against the MIKE+ modelling to determine whether this type of early-stage approach can reliably indicate where subsidence is likely to influence pluvial flood outcomes.

4.6 Scenario analysis and structure of results

The analysis was conducted through two complementary approaches: a hydrodynamic assessment using two MIKE+ model simulations and a simplified risk assessment based on openly available data. The results of these approaches were subsequently compared to evaluate their correspondence and to inform how simplified risk assessments can be better designed in the future.

The two MIKE+ simulations were based on identical input data, with the exception of the terrain model. The first simulation, referred to as Scenario A, represented current ground conditions without accounting for subsidence. The second simulation, Scenario B, incorporated a future terrain model in which cumulative subsidence over a 100-year horizon has been applied. By comparing the results of the two scenarios, the influence of long-term subsidence on pluvial flood outcomes can be isolated and assessed.

The results are presented in the following order. First, the MIKE+ results are presented through a comparison of the two scenarios, including spatial differences in water depth, flux, and velocity in order to address Objective 2. Areas exhibiting spatially coherent impacts, such as changed water depths or flow magnitudes, are subsequently identified and described. One of these areas is then investigated in greater detail. This area is selected as it exhibits a range of different flood responses to subsidence, including increases and decreases in water depth, changes in flow direction, and varying subsidence magnitudes, making it representative of the broader mechanisms observed across the study area. The investigation examines the relationship between subsidence magnitude and change in inundation depth through a ratio analysis, the interaction between topography, subsidence, and wa-

ter depth through a transect analysis, and changes in flow direction through a flux analysis. Secondly, spatial differences in water depth was compared to magnitude of subsidence, topography, and soil conditions in order to help address Objective 3. Together, these analyses provide a basis for examining how subsidence influences flood behaviour across multiple spatial scales, from broad area-wide patterns to detailed street-level responses. Lastly, the results of the simplified risk assessment is presented, identifying potential areas of concern based on InSAR data, topography, and soil conditions. The results from the simplified risk assessment are then compared to the MIKE+ results to assess their spatial correspondence and to evaluate the potential of the simplified risk assessment as a first-stage assessment tool, in order to address Objective 4.

5. Results

The following chapter present the results from the two complementary approaches. Sections 5.1, 5.2, and 5.3 present results from the MIKE+ analysis, while Section 5.4 presents the results from the simplified risk assessment.

5.1 Spatial flood response to subsidence

The two models constructed in MIKE+ were used to compare differences in maximum inundation depth, velocity, and flux between the base scenario (A) and the subsidence scenario (B). The results are presented through spatial difference maps and aggregated statistics, with the aim of identifying areas where subsidence has a notable impact on urban flooding.

5.1.1 Water depth

The difference in maximum water depth between Scenario B and Scenario A is presented in Figure 5.1, where green areas indicate locations with a greater maximum inundation depth in Scenario B compared to Scenario A, and red areas indicate locations with a lesser maximum inundation depth in Scenario B compared to Scenario A. The separate water depth results for Scenario A and Scenario B is presented in Appendix 2.

The majority of the study area shows negligible depth differences in the range of -1 to 1 cm, predominantly in areas where the magnitude of subsidence is close to zero, as shown in Figure 5.2. Small differences in maximum water depth, corresponding to ± 1 to 10 cm are the most spatially prevalent beyond the negligible class, distributed along streets and open surfaces. Moderate to large differences exceeding ± 10 cm are less frequent and appear as isolated patches, spatially correlated with areas of greater magnitude of subsidence according to Figure 5.2.

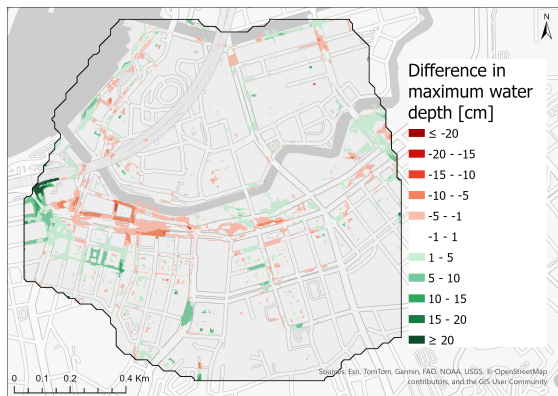


Figure 5.1: Difference in maximum water depth [cm] between Scenario B and Scenario A. Green areas indicate locations with a greater maximum inundation depth in Scenario B.

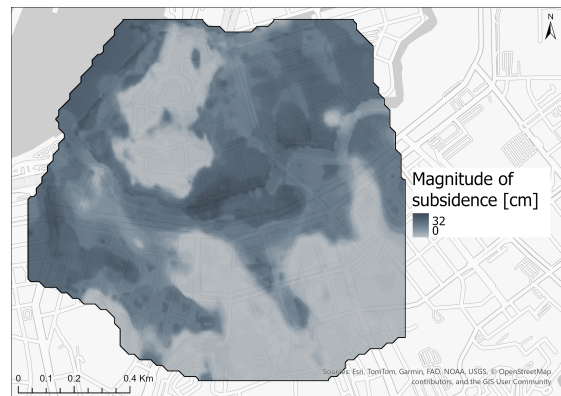


Figure 5.2: Magnitude of subsidence [cm].

Table 5.1 presents the variation in inundation depth between the two scenarios. Areas flooded with less than 20 cm decrease by approximately 3600 m² in Scenario B, representing a difference of 0.29 %. For all inundation depths greater than 20 cm, the flooded area increases in Scenario B, with absolute differences ranging from 117 m² to 1963 m². The percentage differences generally increase with depth, ranging from 2.74 % to 6.60 %, with the exception of the >100 cm interval which shows a slightly lower relative difference of 3.98 %.

Table 5.1: Flooded area [m²] per water depth class for Scenario A and Scenario B, including the absolute and relative difference between the two scenarios. Negative values indicate a greater flooded area in Scenario A, whereas positive values indicate a greater flooded area in Scenario B.

Water depth [cm]	Scenario A [m ²]	Scenario B [m ²]	Difference [m ²]	Difference [%]
< 20	1257450	1253857	-3593	-0.29
20–40	71638	73601	1963	2.74
40–60	16999	17730	731	4.30
60–100	5821	6205	384	6.60
> 100	2936	3053	117	3.98

Figure 5.3 illustrates areas inundated with 20 cm or more, where grey areas are flooded in both scenarios, red areas are flooded exclusively in Scenario A, and green areas represent new inundation appearing exclusively in Scenario B. Figure 5.4 shows the longitudinal transect, marked out in Figure 5.3, presenting the maximum water depth for both scenarios along the profile. The transect illustrates that the water depth exceeds the 20 cm threshold along parts of the road in Scenario B that are below 20 cm in Scenario A. These parts of the transect are therefore green in Figure 5.3.

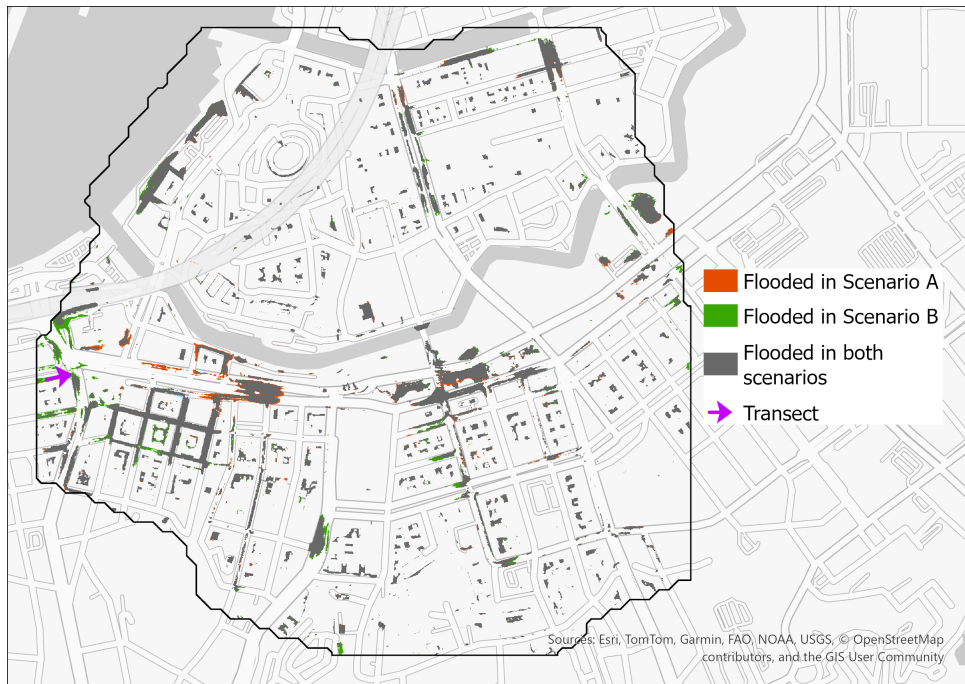


Figure 5.3: Map of areas flooded with 20 cm water or more in the scenarios. The grey areas are flooded in both scenarios, the red areas are flooded in Scenario A but not in Scenario B, and the green areas are flooded only in Scenario B. The purple arrow marks the location and direction of the transect.

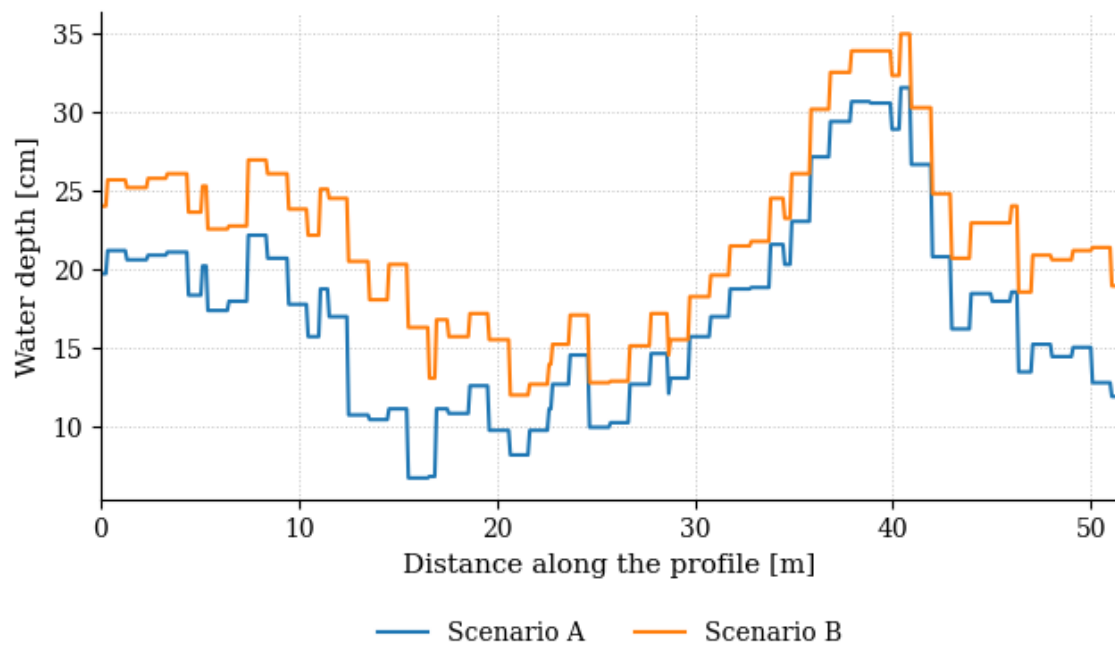


Figure 5.4: Longitudinal profile of maximum water depth for Scenario A and Scenario B, where the distance is measured from the starting point of the profile.

5.1.2 Velocity and Flux

The difference in velocity [m/s] between Scenario B and Scenario A is illustrated in Figure 5.5, where green areas indicate an increase in velocity in Scenario B compared to Scenario A and red areas indicate a decrease. The majority of the differences are distributed along the street network. No distinctive spatial correlation between the difference in velocity and the magnitude of subsidence is evident from a comparison of Figure 5.5 and Figure 5.6.

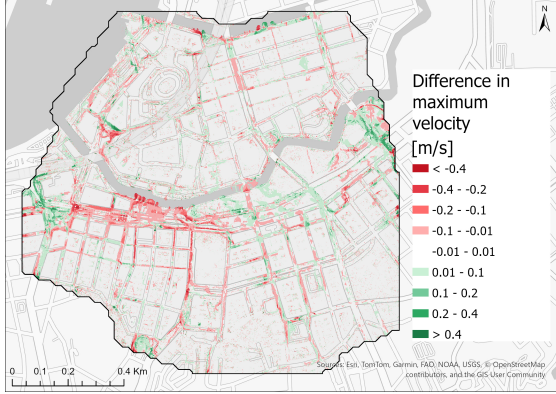


Figure 5.5: Difference in maximum velocity [m/s] between Scenario B and Scenario A. Green areas indicate locations with a greater maximum velocity in Scenario B.

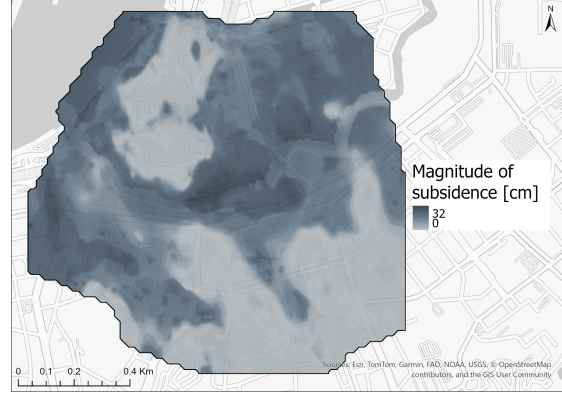


Figure 5.6: Magnitude of subsidence [cm].

The velocity distribution across different intervals for both scenarios is presented in Table 5.2. The majority of the velocity intervals show relative differences of less than 1 % between the two scenarios. The most notable relative change is found in the >5 m/s interval, with a decrease of 6.54 %, however this interval covers a very small total area of 153 m² in Scenario A and 143 m² in Scenario B and should therefore be interpreted with caution.

Table 5.2: Affected area [m²] per velocity class [m/s] for Scenario A and Scenario B, including the absolute and relative difference between the two scenarios. Negative values indicate a greater affected area in Scenario A, whereas positive values indicate a greater affected area in Scenario B.

Velocity [m/s]	Scenario A [m ²]	Scenario B [m ²]	Difference [m ²]	Difference [%]
0–0.5	1171651	1172580	929	0.08
0.5–1	102609	101523	-1086	-1.06
1–2	63187	62797	-390	-0.62
2–5	17244	17403	159	0.92
> 5	153	143	-10	-6.54

Figure 5.7 presents the spatial distribution of differences in maximum flux [L/s/m]

between the two scenarios. The majority of differences lie within the range of 0 to 50 L/s/m, widely distributed along the street network. Larger differences in the range of 50 to 100 L/s/m are more spatially concentrated, appearing distinctly along certain streets. Differences exceeding 100 L/s/m are limited in spatial extent and appear as isolated patches. No distinctive spatial correlation between the difference in flux and the magnitude of subsidence is evident from a comparison of Figure 5.7 and Figure 5.8.

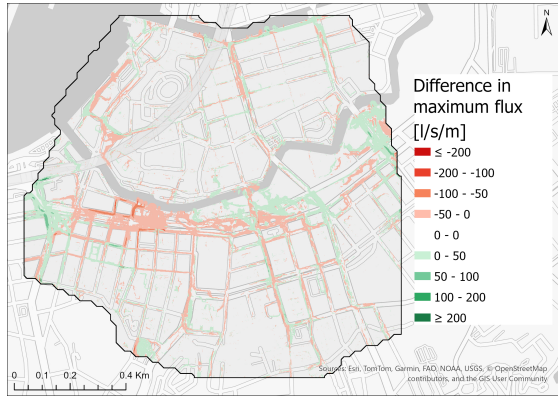


Figure 5.7: Difference in maximum flux [L/s/m] between Scenario B and Scenario A. Green areas indicate locations with a greater maximum flux in Scenario B.

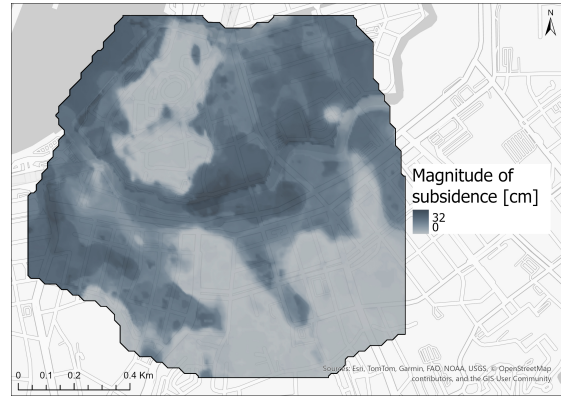


Figure 5.8: Magnitude of subsidence [cm].

Table 5.3 presents the aggregated flux statistics between the two scenarios. The relative differences are generally small across the majority of the study area, with the most pronounced changes occurring in the higher flux intervals. However, the total area in the two highest intervals is very small and the results should therefore be interpreted with caution.

Table 5.3: Affected area [m²] per flux class [L/s/m] for Scenario A and Scenario B, including the absolute and relative difference between the two scenarios. Negative values indicate a greater affected area in Scenario A, whereas positive values indicate a greater affected area in Scenario B.

Flux [L/s/m]	Scenario A [m ²]	Scenario B [m ²]	Difference [m ²]	Difference [%]
< 10	1073611	1071554	-2057	-0.19
10–250	263610	265541	1931	0.73
250–500	14352	14144	-208	-1.45
500–750	3138	3055	-83	-2.64
> 750	103	124	21	20.39

5.1.3 Investigation of affected areas

Based on the difference in inundation depth (Figure 5.1) and the spatial distribution of areas flooded with 20 cm or more (Figure 5.3), six areas potentially affected by subsidence were identified for further investigation, as marked in Figure 5.9. These areas were selected on the basis of two criteria: they exhibit a relatively large difference in maximum inundation depth between Scenario B and Scenario A, and they correspond to locations where inundation above 20 cm was either gained or lost between the two scenarios.

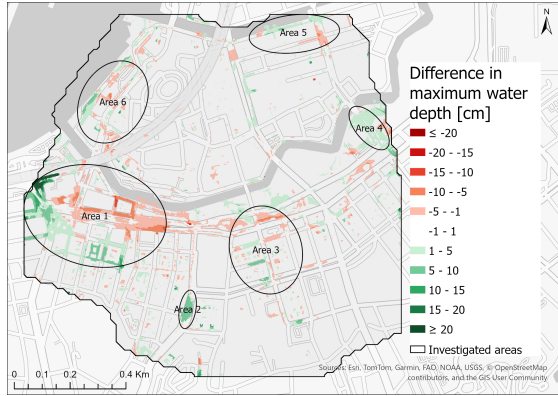


Figure 5.9: Identification of problem areas based on difference in water depth between Scenario B and Scenario A.

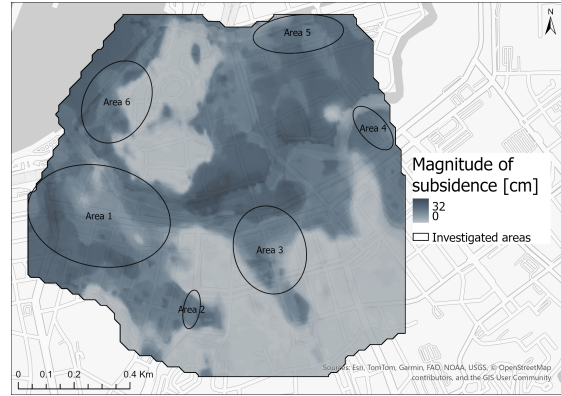


Figure 5.10: Magnitude of subsidence [cm] within the case study area, showing the locations of the six investigated areas.

The western part of Area 1 is characterised by an increase in maximum inundation depth in Scenario B (Figure 5.9). A greater extent of the roads also receive a water depth exceeding 20 cm in Scenario B compared to Scenario A (Figure 5.3). The north-west part of Area 1 exhibits one of the greatest differences in maximum depth within the entire case study area. The greatest subsidence magnitudes, reaching up to 32 cm, are also concentrated in the northern part of Area 1 (Figure 5.10).

The central part of Area 1, comprising Haga, has primarily received an increase in maximum inundation depth ranging from 1 to 15 cm. An expansion of flooded areas is also observed (Figure 5.3), however most of the area is flooded with 20 cm or more in both scenarios. The difference in maximum flux is predominantly within the ± 0 to 50 L/s/m range, however a few flow paths exhibit differences in the range of 50 to 100 L/s/m and -50 to -100 L/s/m respectively (Figure 5.7).

The northern part of Area 1 exhibits a decrease in maximum inundation depth ranging from -1 to -15 cm (Figure 5.9), as well as a reduction in areas flooded with more than 20 cm (Figure 5.3). Maximum flux has decreased by 50 to 100 L/s/m along several flow paths, with localised reductions of 100 to 200 L/s/m (Figure 5.7).

Area 2 consists solely of increased maximum water depth in the range of 5 to 10 cm and exhibits some expansion of adjacent flooded areas in Scenario B. Area 2 is located within the zone of moderate subsidence magnitudes (Figure 5.10). In addition, the area is situated in a pronounced topographical depression.

Area 3 exhibits both increases and decreases in maximum inundation depth, as well as expansion and reduction of flooded areas (Figures 5.1 and 5.3). The expansion of flooded areas is primarily concentrated along the road network, whereas

the reduction occurs downstream in vegetated areas between two major roads. Differences in water depth range from ± 1 to 10 cm. Maximum flux increases along streets where water depth has increased, whereas the street conveying water towards the vegetated area exhibits a corresponding decrease in maximum flux (Figure 5.7). The total volume reaching the vegetated area decreases by 455 m³.

Area 4 received a minor increase in inundation depth of 1 to 5 cm in Scenario B along the street, accompanied by a limited expansion of areas inundated to depths exceeding 20 cm in the adjacent vegetated areas (Figures 5.9 and 5.3). Both flux and velocity increased in Scenario B (Figures 5.7 and 5.5), a noticeable increase in velocity along the street. The peak flux along the street increased from 2140 L/s in Scenario A to 2850 L/s in Scenario B, corresponding to an increase of 33 %. Despite this substantial increase in peak flux and flow velocity, the change in inundation extent remained minor. The area is adjacent to Rosenlundskanalen to the north, towards which the terrain slopes, allowing surface runoff to be conveyed out of the area.

Area 5 exhibits both an increase and decrease in maximum inundation depth in Scenario B compared to Scenario A (Figure 5.9). The decrease corresponds to a reduction in areas flooded with more than 20 cm, whereas the increase corresponds to a minor expansion of such areas (Figure 5.3). However, large parts of the affected roads are flooded with 20 cm or more in both scenarios.

Area 6 is similar to Area 5 in that the areas flooded with more than 20 cm appear to have shifted spatially rather than changed significantly in total extent (Figure 5.3). The difference in inundation depth is predominantly within the ± 1 to 5 cm interval, with one larger area exhibiting an increase of 5 to 10 cm (Figure 5.9). The difference in maximum flux is within ± 0 to 50 , with a change of the direction of the flux in the southern part of the area (Figure 5.7). Upstream of the divergence point, flow and volume remain largely unchanged between the two scenarios. However, at the divergence point the water takes a different path in Scenario B, with a substantially greater share of the total volume shifting from a southward to a westward direction.

5.2 Magnitude of subsidence and flood behaviour

This section provides a more detailed investigation of flood behaviour within Area 1, which was identified as one of the areas most significantly affected in the preceding analysis. Area 1 is also considered representative of the types of flood behaviour changes observed across the broader case study area.

5.2.1 Subsidence magnitude and inundation depth

To quantify the relationship between subsidence magnitude and changes in pluvial flood inundation, ten points were sampled across the case study area and analysed in terms of subsidence magnitude and corresponding change in maximum water depth. The locations of the sampled points are shown in Figure 5.11, and the resulting ratios between subsidence magnitude and change in maximum water depth are presented in Table 5.4 and Figure 5.12. The results show considerable variation, with similar subsidence magnitudes yielding different changes in water depth. For example, a subsidence of approximately 15 to 16 cm corresponds to changes in maximum water

depth ranging from -2.0 to 6.7 cm. Furthermore, four of the sampled points (7, 8, 9 and 10) exhibit a negative change in inundation depth despite experiencing subsidence. The majority of points show a ratio below 0.5, while point 9 stands out with a ratio of -1.08. As seen in Figure 5.12, no clear linear relationship is observed between subsidence magnitude and change in inundation depth.

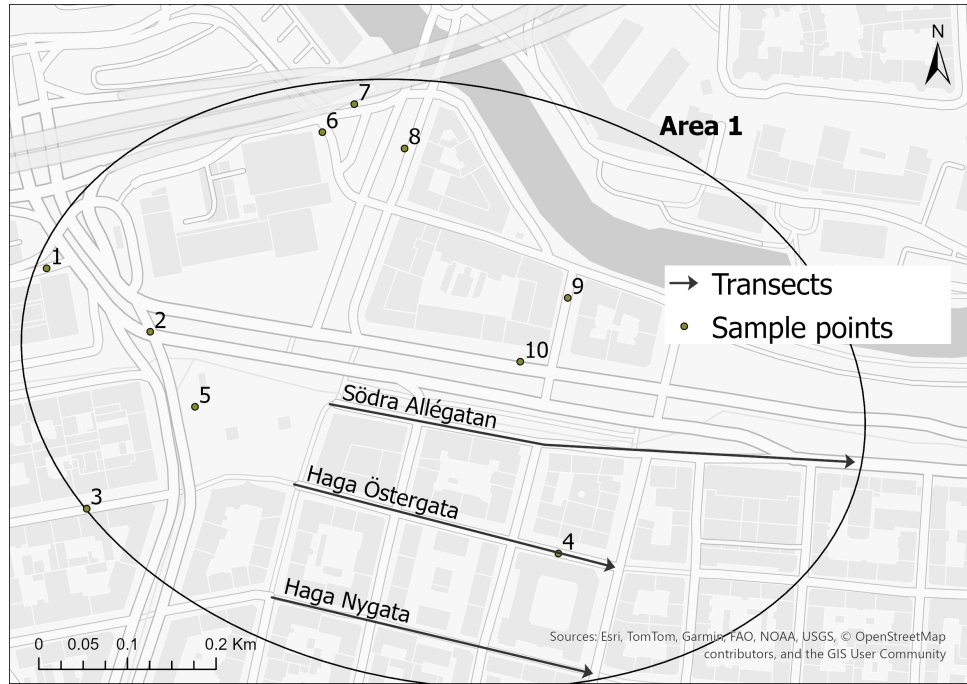


Figure 5.11: Location of sample points (1-10) and transects of Södra Allégatan, Haga Östergata and Haga Nygata.

Table 5.4: Magnitude of subsidence, change in inundation depth and the ratio between the two for ten points in Area 1.

Point	Subsidence [cm]	Change in inundation depth [cm]	Ratio [-]
1	16.1	6.7	0.41
2	26.5	3.6	0.14
3	21.7	6.1	0.28
4	18.7	3.2	0.17
5	28.2	6.5	0.23
6	17.6	3.2	0.18
7	14.8	-2.0	-0.13
8	6.6	-2.7	-0.41
9	12.4	-13.4	-1.08
10	11.0	-4.0	-0.36

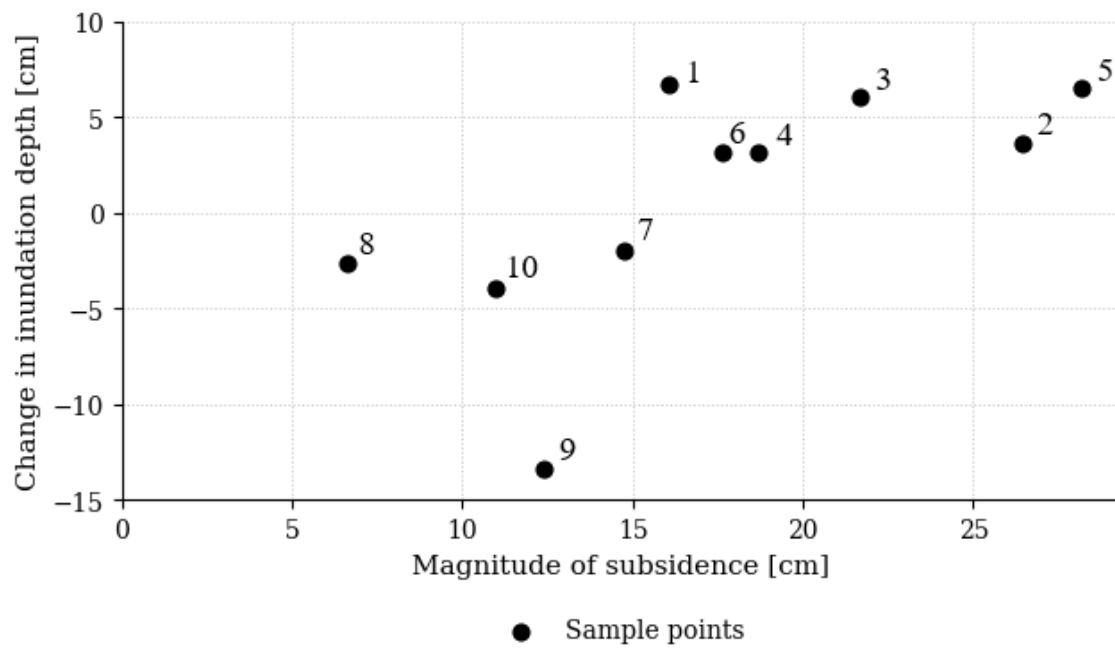


Figure 5.12: Change in inundation depth as a function of subsidence magnitude for the sampled points within Area 1.

5.2.2 Transect analysis

Ground elevation and maximum water depth profiles were extracted along three road transects within Area 1: Södra Allégatan, Haga Östergata, and Haga Nygata, as shown in Figure 5.11.

Figure 5.13 presents the ground elevation and maximum water depth for Scenario A and B along Södra Allégatan. Along the first 150 m of the transect, the two DEM profiles maintain a relatively consistent separation, indicating a broadly uniform distribution of subsidence, and the difference in maximum water depth between the scenarios remains modest throughout this section. Beyond approximately 150 m, the terrain begins to slope more steeply, transitioning into a pronounced local depression that reaches its lowest point around 280 to 300 m. In this section, the DEM profiles diverge, and the corresponding difference in maximum water depth increases markedly, with Scenario A exhibiting substantially greater water depths than Scenario B.

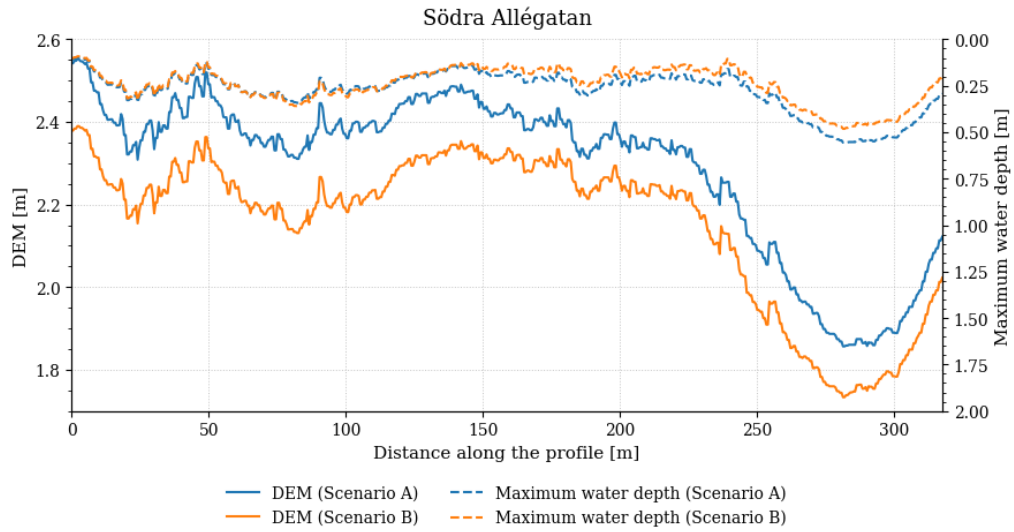


Figure 5.13: Ground elevation (DEM) and maximum water depth profiles along Södra Allégatan for Scenario A and Scenario B. The right y-axis is inverted to facilitate visual comparison between ground elevation and maximum water depth.

Figure 5.14 presents the profiles along Haga Östergata. Along the first 270 m, the two DEM profiles maintain a relatively consistent separation, and small but discernible differences in maximum water depth are observed between the scenarios throughout this section. Beyond approximately 270 m, the terrain rises clearly and the DEM profiles converge, indicating considerably less subsidence in this elevated section. Correspondingly, the difference in maximum water depth between the scenarios diminishes markedly in this part of the transect.

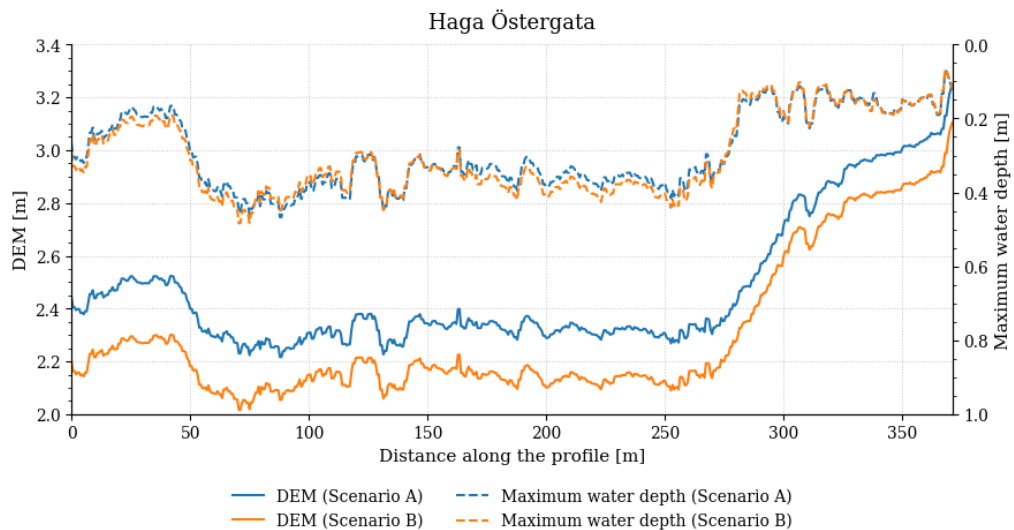


Figure 5.14: Ground elevation (DEM) and maximum water depth profiles along Haga Östergata for Scenario A and Scenario B. The right y-axis is inverted to facilitate visual comparison between ground elevation and maximum water depth.

Figure 5.15 presents the profiles along Haga Nygata. The two DEM profiles

maintain a relatively consistent separation along the entire transect, indicating a spatially uniform distribution of subsidence. The difference in maximum water depth between the scenarios is present throughout, including at the elevated section in the middle of the transect, but increases towards the end where the terrain begins to slope downward.

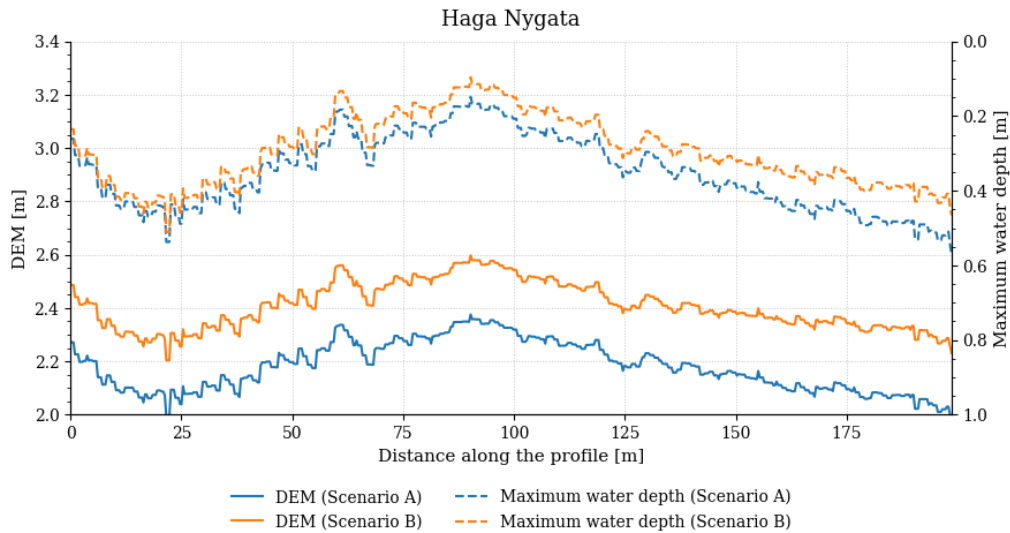


Figure 5.15: Ground elevation (DEM) and maximum water depth profiles along Haga Nygata for Scenario A and Scenario B. The right y-axis is inverted to facilitate visual comparison between ground elevation and maximum water depth.

5.2.3 Flow analysis

The flow analysis presented in Figure 5.16 further reflects the patterns described above. The green arrows in the figure represent the flow direction for Scenario A, whereas the yellow arrows represent the flow direction for Scenario B. Along all three streets, the dominant flow direction shifts from west to east in Scenario A to east to west in Scenario B.

The corresponding flow rates and volumes in Table 5.5 and Table 5.6 show that along Haga Östergata, only eastward flow is recorded in Scenario A, whereas a westward reverse flow appears in Scenario B and the total volume decreases significantly. At Haga Nygata, eastward flow decreases while westward flow increases, and both volumes increase in Scenario B. At Södra Allégatan, no eastward flow is recorded in Scenario B, and the westward volume increases considerably.

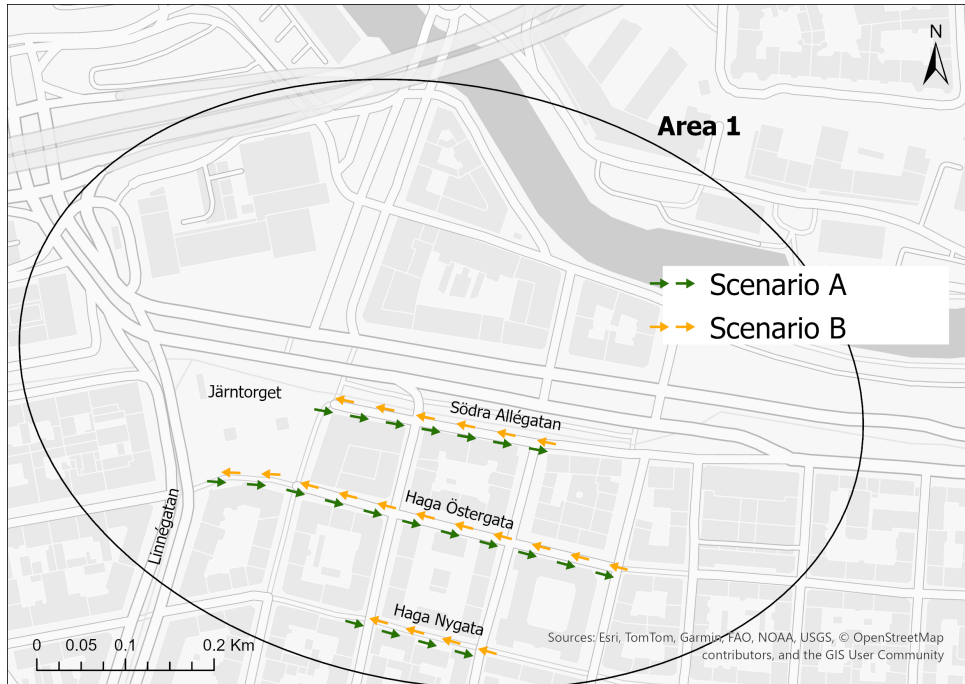


Figure 5.16: Flow direction of the largest flow along the investigated streets in Area 1 (Södra Allégatan, Haga Östergata, and Haga Nygata) for Scenario A (green) and Scenario B (yellow).

Table 5.5: Flow [m^3/s] for Scenario A and B on transects in Area 1.

Location	Scenario A		Scenario B	
	Eastward	Westward	Eastward	Westward
Haga Nygata	0.081	0.008	0.056	0.13
Haga Östergata	0.80		0.32	0.36
Södra Allégatan	0.051	0.048		0.17

Table 5.6: Volume [m^3] of water for Scenario A and B on transects in Area 1.

Location	Scenario A		Scenario B	
	Eastward	Westward	Eastward	Westward
Haga Nygata	880	14	1149	236
Haga Östergata	18476		6778	750
Södra Allégatan	616	216		1019

5.3 Flood behaviour and terrain characteristics

Figure 5.17 presents the spatial distribution of differences in maximum water depth between the two scenarios, overlaid on the magnitude of subsidence. Differences in water depth exceeding ± 1 cm exhibit a strong spatial correlation with areas where

the magnitude of subsidence exceeds 0 cm.

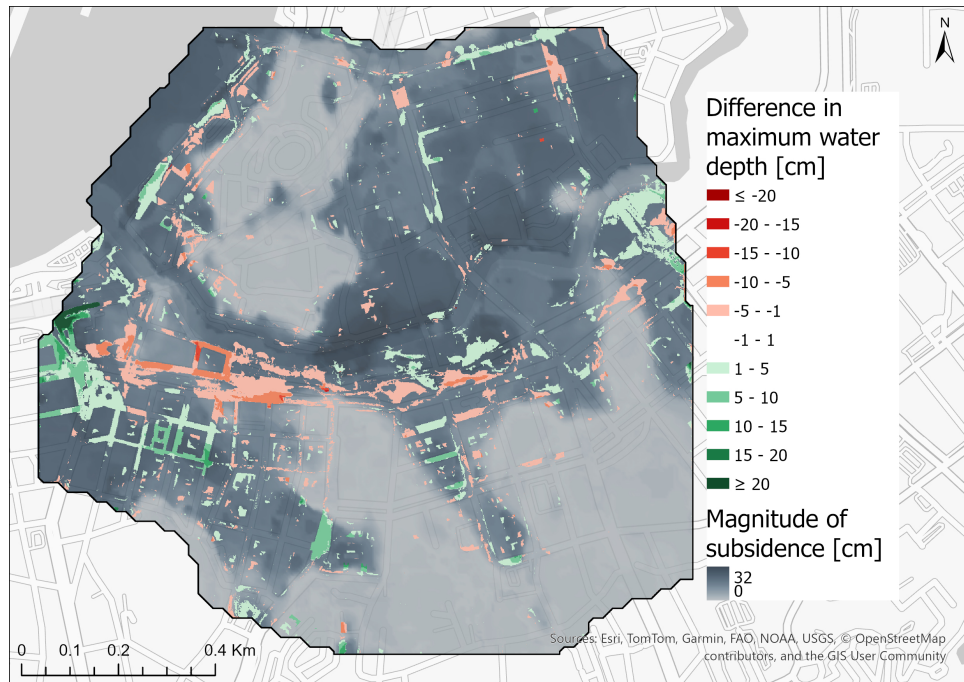


Figure 5.17: Difference in maximum water depth [cm] underlain by the magnitude of subsidence [cm].

Likewise, Figure 5.18 presents the spatial distribution of differences in maximum water depth underlain by topography. The most pronounced differences in water depth are located in areas of low topography and/or depressions.

Figure 5.19 presents the spatial distribution of differences in maximum water depth underlain by soil depth. A correlation between larger differences in maximum water depth and thick layers of soil can be noted, especially in the west of the study area. Areas with 0 to 10 m of soil depth have no or limited effect of changes in maximum water depth when subsidence is introduced.

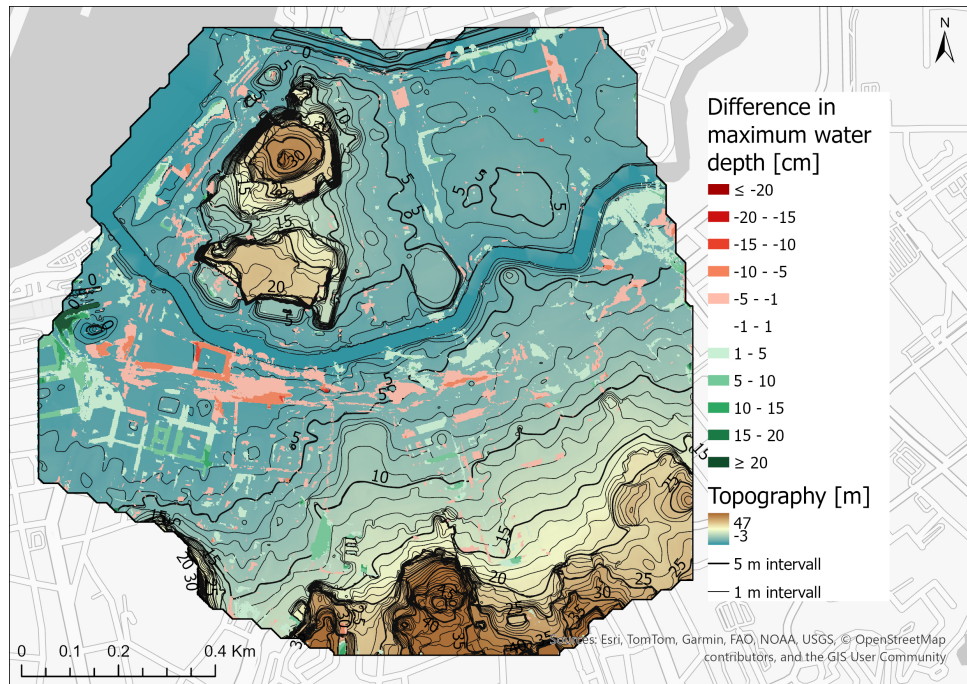


Figure 5.18: Difference in maximum water depth [cm] underlain by topography and topographic lines.

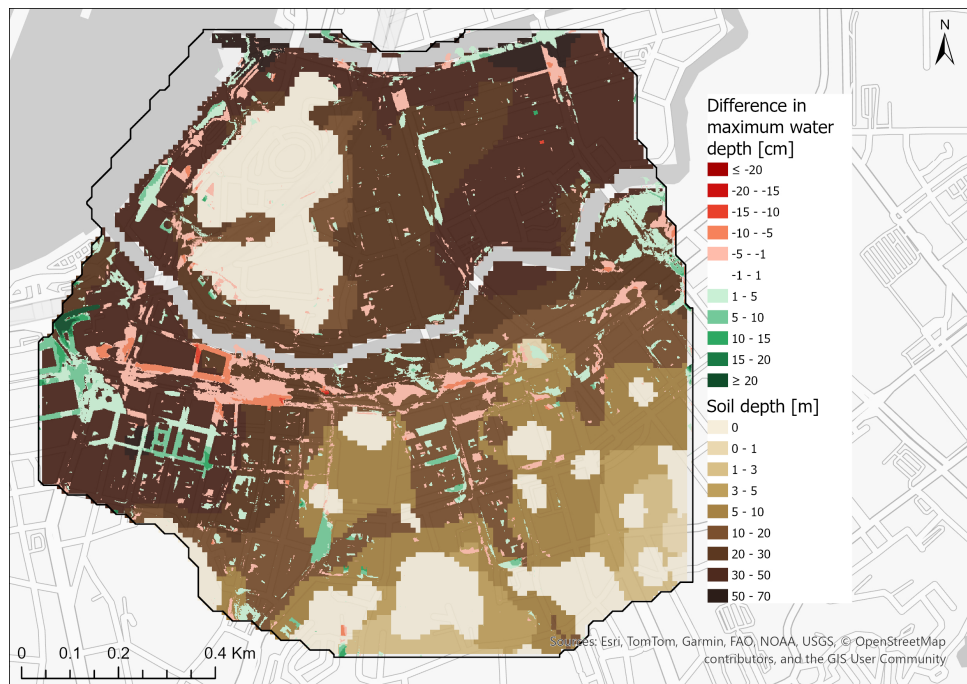


Figure 5.19: Difference in maximum water depth [cm] underlain by soil depth [m] to bedrock.

5.4 Simplified risk assessment

Based on the InSAR data, three areas exhibiting larger, spatially coherent negative line-of-sight displacement, indicative of ongoing subsidence, were identified and are

presented in Figure 5.20. These areas exhibit the highest rates of measured ground movement within the case study area.

As established in Section 3.2, a spatial correspondence between low-lying terrain and deep clay deposits exists within the case study area, and all three identified risk areas coincide with locations exhibiting these characteristics. Overlay figures of InSAR data and soil classification, topography and soil depths are provided in Appendix 3.

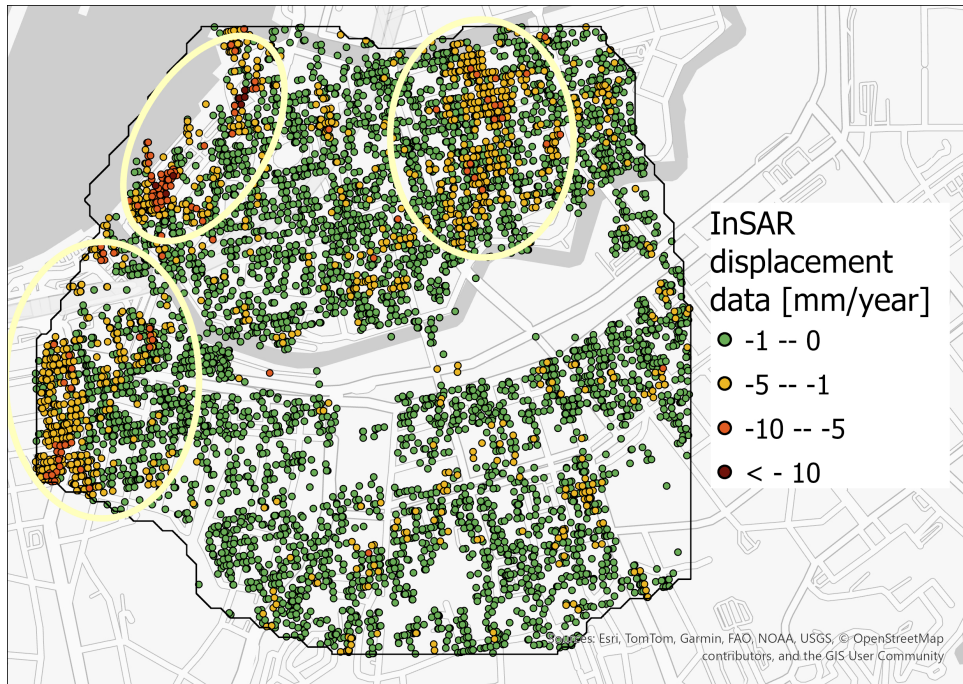


Figure 5.20: Identified areas prone to subsidence from InSAR subsidence data (Swedish Geotechnical Institute, 2026a).

Comparing the flood results of Scenario A, Figure 5.21, with the identified subsidence zones, a spatial overlap is evident, particularly in the western part of the study area, where areas of maximum water depth exceeding 20 cm coincide with the highest subsidence rates. However, areas of water accumulation are also found outside the zones of greatest subsidence.

The simplified analysis identifies a spatial correlation between areas of ongoing subsidence, low surface elevations, and soil conditions prone to long-term subsidence. Furthermore, the cloudburst mapping reveals that several parts of the study area are already exposed to flood risk, with a notable overlap between flood-prone areas and the identified subsidence zones.

5.4.1 The simplified risk assessment against MIKE+ results

Figure 5.22 and Figure 5.23 are presented side by side to enable a direct comparison between the spatial distribution of subsidence-induced changes in maximum water depth and the areas identified as prone to subsidence in the simplified risk assessment. A spatial overlap is observed in the south-western part of the study area, where the most pronounced differences in maximum water depth are evident. The north-western area also shows changes in maximum water depth. Notably,

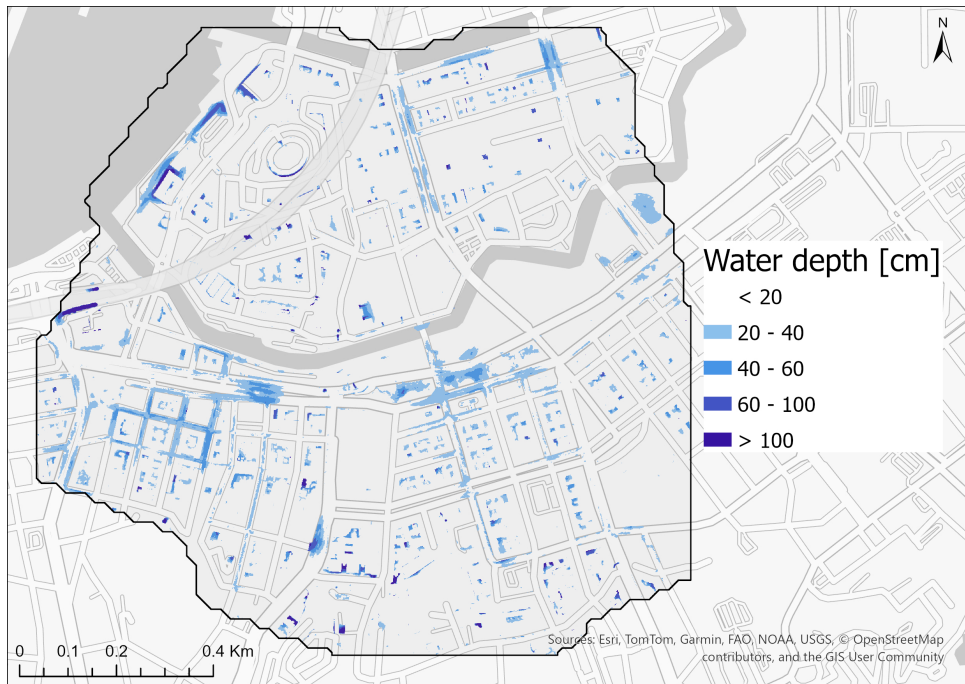


Figure 5.21: Results of maximum water depth [cm] for Scenario A.

both areas exhibits both increases and decreases in water depth. Conversely, the north-eastern area identified as subsidence-prone in Figure 5.23 shows little to no difference in maximum water depth between the two scenarios. Furthermore, differences in maximum water depth are also evident in areas beyond those identified as primary subsidence zones in the simplified risk assessment.

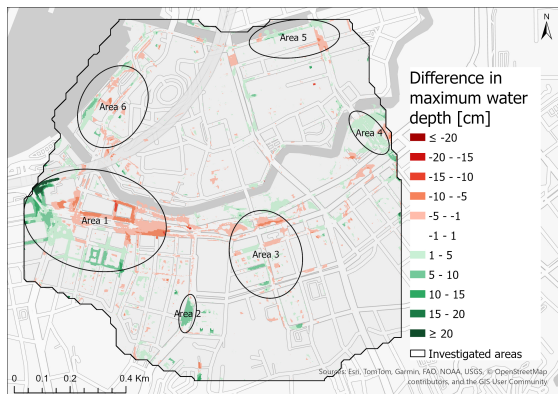


Figure 5.22: Difference in maximum depth [m] between the two models with problem areas circled.

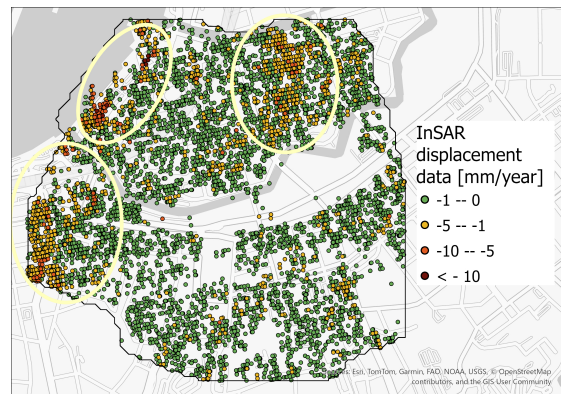


Figure 5.23: Identified areas prone to subsidence from InSAR subsidence data (Swedish Geotechnical Institute, 2026a).

6. Discussion

This chapter discusses the findings of the study in relation to its objectives. First, the results of the MIKE+ modelling are discussed to examine how subsidence influences flood behaviour, with particular attention to the role of terrain characteristics, soil conditions, and the spatial pattern of subsidence. The insights gained from this analysis are then used to evaluate and refine the simplified risk assessment as an early-stage screening tool. Finally, the limitations of the study are addressed, along with societal implications and suggestions for future research.

6.1 The influence of subsidence on flood behaviour

This chapter discusses the findings of the MIKE+ modelling to address Objectives 2 and 3: how the inclusion of predicted subsidence affects the spatial distribution of flooding, water depths, and flow paths, and whether low-lying areas underlain by subsidence-prone soils are systematically more exposed to altered flood conditions.

6.1.1 Spatial flood response and terrain characteristics

The comparison between the two scenarios reveals that subsidence influences pluvial flood outcomes widespread across the study area, although the nature and magnitude of the influence varies considerably between locations. One pattern is the one of gradual expansion. Areas already identified as flood-prone under current conditions, Scenario A, tend to grow in spatial extent under Scenario B, rather than new problem areas emerging entirely independently. Similarly, areas showing reduced flood exposure in Scenario B generally shrink rather than disappear altogether. This suggests that subsidence primarily acts to amplify existing vulnerabilities rather than to fundamentally restructure the spatial distribution of flooding. However, for some areas, such as the area south-west seen in Figure 5.3, the extension of the flooded area is quite large in Scenario B. From a planning perspective, this distinction is significant, the expansion of existing problem areas affects infrastructure and measures already planned or being planned, whereas the emergence of entirely new flood-prone areas represents locations where no mitigation would currently be warranted.

The spatial distribution of affected areas shows a clear correspondence with the underlying terrain characteristics. The areas exhibiting the most pronounced changes in maximum water depth consistently coincide with low-lying terrain or local topographic depressions that are subject to ongoing subsidence. This is especially illustrated in the north eastern part of the study area, where Figure 5.2 shows ongoing subsidence, but Figure 5.1 shows no to moderate change in flood depths. Looking at Figure 5.18, this area seems to be a local elevation. Further on, it is worth noting that subsidence in one area can influence flood outcomes in adjacent areas, as changes in surface gradients redirect runoff across broader zones. The pronounced subsidence observed in the Linné and Haga district, for instance, appears to contribute to altered flood behaviour in neighbouring Södra Allégatan, illustrating that the spatial influence of subsidence extends beyond the zone of ground

movement itself.

Beyond water depth, the results for flow velocity and flux direction further illustrate the influence of subsidence. Changes in surface gradients drive increases or decreases in flow velocity, and flow directions can reverse entirely, redistributing water towards areas that were previously less exposed. The flux analysis in Section 5.2.3 illustrates this clearly: in Area 1, flow that previously moved away from Linné reverses direction in the subsidence scenario, directing water towards the Linné area instead. This redistribution of surface runoff may partly explain the worsening flood conditions observed in Linné under Scenario B, and highlights that the consequences of subsidence extend beyond the zone or magnitude of ground movement itself. Area 4 is situated adjacent to and slopes towards Rosenlundskanalen, and this topographic gradient appears to limit the spatial expansion of inundated areas in the subsidence scenario, as additional runoff is directed towards the canal rather than accumulating on the street surface. In this sense, the topography acts favourably by channelling water away from the urban environment. However, Area 4 constitutes an important arterial road, and the increased volumes of water conveyed along this route, even if ultimately discharged into the canal, may exceed the threshold for safe passage, compromising accessibility and emergency response capacity. The topographic advantage of draining towards a watercourse therefore does not preclude significant consequences if flow rates increase sufficiently.

In addition, areas subject to changes in flood behaviour are also consistently underlain by deep deposits of clay, as can be seen in Figure 5.19. Although clay depth was not used as a direct model input, the observed spatial correlation between deep clay deposits, subsidence, and altered flood behaviour suggests that clay depth may serve as an indicator of areas where subsidence has the potential to significantly influence flooding conditions.

Taken together, the results demonstrate that the influence of subsidence on pluvial flood outcomes is governed by the interplay between topography, soil conditions, and the magnitude and spatial pattern of ground movement. These factors do not act independently, rather, it is their combined configuration that determines where and to what extent flood behaviour changes. This complexity means that equal magnitudes of subsidence can produce fundamentally different flood consequences depending on the local terrain and soil conditions, making it difficult to predict problem areas without accounting for all contributing factors simultaneously. While the overall flood picture is generally one of amplification or attenuation of existing conditions rather than a wholesale restructuring of flood patterns, the changes are nonetheless real. This complexity underscores the value of incorporating subsidence into hydrodynamic modelling. By adjusting the terrain to reflect projected future ground conditions, a MIKE+ analysis can capture these interactions and identify how flood behaviour is likely to evolve, in a way that simpler screening approaches cannot.

6.1.2 Magnitude of subsidence and flood response

The ratio analysis conducted across the sampled points in Area 1 illustrates the complexity of the relationship between subsidence magnitude and change in maximum water depth. Despite the points being located within the same area, characterised

by broadly similar topography, clay depth, and subsidence magnitudes, the resulting changes in water depth vary considerably between points, and non linear relationship is observed. This highlights that even small spatial differences in local terrain, soil conditions, or the relative magnitude of subsidence between neighbouring locations can produce markedly different flood outcomes. Crucially, a large subsidence magnitude does not necessarily translate into a proportional increase in water depth. In some cases, subsidence can even result in a decrease in maximum water depth at a given location, if the surrounding terrain settles more and redirects runoff away from that point. This non-linearity underscores the complexity of the relationship between ground movement and flood response, and suggests that subsidence magnitude alone is an insufficient basis for predicting where flood conditions will worsen.

The transect analyses along Södra Allégatan, Haga Östergata, and Haga Nygata further illustrate this complexity and provide insight into the mechanisms driving local flood response. Along Södra Allégatan, where subsidence is spatially variable, the DEM profiles diverge beyond the transition zone, steepening local surface gradients and redirecting runoff towards the topographic depression at the end of the transect. It is at this transition between zones of differing subsidence rates, rather than at the point of greatest absolute subsidence, where the change in flood behaviour first becomes apparent, and where the most pronounced differences in maximum water depth are observed. Along Haga Nygata, where subsidence is spatially uniform, the DEM profiles remain largely parallel throughout the transect, and the difference in maximum water depth increases consistently without any notable change in flood behaviour. Across all three transects, the difference in maximum water depth is most pronounced where the terrain is lowest, regardless of whether subsidence is spatially variable or uniform. This suggests that existing topographic lows act as concentrating features that amplify the effects of subsidence on flood depth.

These findings are consistent with those of Yin et al. (2016) and Jiang et al. (2023), who concluded that local flood response to subsidence is governed by relative relief to the surrounding area rather than the absolute magnitude of ground movement. Where subsidence is spatially variable, differential ground movement alters local surface gradients and redistributes runoff, potentially directing water towards areas that were previously less exposed. Where subsidence is uniform, the relative configuration of the terrain is preserved, and flood patterns remain broadly unchanged even as absolute water depths increase. In summary, the ratio analysis and transect analyses demonstrate that the influence of subsidence on pluvial flood outcomes is inherently local, shaped by the interplay between subsidence magnitude, spatial variability of ground movement, and underlying topography and soil conditions.

6.2 Evaluating the simplified risk assessment

The simplified risk assessment was designed to serve as an accessible screening tool applicable in early planning stages, where a full hydrodynamic modelling assessment is not yet warranted. Its purpose is not to replicate the results of a MIKE+ modelling analysis, but rather to provide a first indication of whether subsidence is likely to be relevant to pluvial flood outcomes in a given area. The two approaches should

therefore be understood as complementary tools operating at different stages of a planning process, not as competing methods.

Comparing the results of the simplified risk assessment with the MIKE+ modelling reveals a partial spatial correspondence. The south-western area identified as subsidence-prone showed clear overlap with areas exhibiting pronounced changes in maximum water depth, lending support to the utility of the screening approach. However, the north-eastern area identified as subsidence-prone showed little to no difference in maximum water depth between the two scenarios. This area is situated on a local topographic high, which may partly explain why subsidence here did not translate into altered flood outcomes, the relative relief to surrounding areas remains such that runoff is not concentrated or redirected. This illustrates that while it may seem intuitive that larger subsidence magnitudes would lead to more pronounced flood impacts, the MIKE+ results demonstrate that this relationship is not straightforward, as discussed in 6.1.2.

The MIKE+ results provide valuable guidance on how a simplified risk assessment of this kind can be better designed. Areas exhibiting altered flood behaviour consistently coincide with the combination of low-lying terrain or local topographic depressions, deep clay deposits, and ongoing subsidence. This suggests that these three factors together constitute a more reliable set of screening indicators than subsidence magnitude alone. However, this relationship is not reversible. The presence of these conditions does not guarantee altered flood outcomes, but where significant changes do occur, these conditions are invariably present. Beyond these baseline indicators, particular attention should be paid to locations where subsidence rates are spatially variable, such as at transitions between soil types or at the edges of deep clay deposits, as differential ground movement is more likely to alter local surface gradients and redistribute runoff. A spatial buffer should also be applied around identified zones, since subsidence in one area can redirect runoff into adjacent areas that may not themselves be subject to significant ground movement.

In practice, applying these refined criteria presents a challenge, as spatial variability in subsidence rates is widespread across the study area, making it difficult to narrow down specific problem zones. This is not a failure of the approach, rather, it reflects an inherent limitation of an early-stage risk assessment of this kind, when the underlying risk factor is spatially pervasive. However, the value of the simplified risk assessment lies not in pinpointing specific locations with certainty, but in identifying where a more detailed investigation is warranted.

A further consideration is that the InSAR data used in the simplified risk assessment reflects historically measured displacement, whereas the MIKE+ modelling projects cumulative subsidence over a 100-year horizon. Using InSAR as a proxy for future subsidence implicitly assumes that ground movement will continue at a similar rate and pattern, which may be reasonable in a densely built urban area but cannot be taken for granted. Additionally, certain areas lack InSAR coverage entirely, and the absence of data should not be interpreted as an absence of risk. For these reasons, geotechnical indicators such as soil type, clay depth, and load history may be more directly informative than displacement measurements alone when assessing long-term subsidence potential.

Taken together, the results suggest that a simplified risk assessment based on to-

pography, soil conditions, and indicators of spatial variability in subsidence potential can serve as a useful first-stage tool. Where low-lying terrain, subsidence-prone soils, and spatially variable subsidence conditions coincide with existing flood risk, a more detailed assessment incorporating subsidence is warranted. However, the screening should be regarded as indicative only. The value lies in identifying where further investigation is needed, not in predicting specific flood outcomes. To develop more robust and transferable guidelines, the combined approach applied in this study would need to be replicated across a wider range of urban contexts with different soil conditions, topographic characteristics, and subsidence patterns.

6.3 Limitations of the study

This section outlines the key limitations of this study, encompassing both modelling choices and data constraints. Several of the limitations identified point towards areas where further research and refinement would be valuable.

Although free-flow boundary conditions were applied at locations where water was expected to leave the model domain, uncertainties remain regarding their performance, and not all boundaries of the hydrodynamic model area are equipped with such conditions. This means that the behaviour of water near the model edges may not fully reflect real-world conditions, and the results in these areas should be interpreted with caution. The area around Götatunneln is situated close to the model boundary, which may partly contribute to the notably high water depths observed there in both scenarios. However, the absence of associated infrastructure, such as pumping stations designed to handle water ingress, is likely an important factor. Absolute water depths near the tunnel should therefore be interpreted with caution. Beyond this modelling limitation, a substantial difference in maximum water depth between the two scenarios is also observed near the tunnel, consistent with the findings in adjacent areas that topographically drain towards Götatunneln. This suggests that greater volumes of surface runoff are directed towards the tunnel under Scenario B, raising the question of whether existing infrastructure would be sufficient to handle the additional inflow resulting from long-term ground movement.

Buildings and enclosed courtyards are not fully represented in the model in a way that allows water to exit through gates and passageways as it would in reality. As a result, water that would realistically drain onto surrounding streets instead accumulates within courtyards, leading to an underestimation of surface flooding on adjacent streets. This limitation applies to both scenarios and therefore has a limited effect on the relative differences between them, though it does mean that absolute flood depths on open streets are likely underestimated throughout the model domain.

Göta Älv, Rosenlundskanalen, and Stora Hamnkanalen are represented through adjustments to the infiltration module rather than as explicit hydrodynamic boundary conditions. While this approach maintains stable water levels and prevents artificial accumulation, it is a deliberate simplification that does not capture the full hydrodynamic interaction between surface runoff and the receiving water bodies. This limitation is related to the broader challenge of model boundaries. The waterways are located within the model domain, making it difficult to define conventional boundary conditions, and the infiltration-based approach was adopted as a practical workaround.

Furthermore, rather than coupling the surface model to a detailed 1D pipe network model, a network reduction was applied to account for the drainage capacity of the underground system. This simplification means that the dynamic interaction between surface flooding and the pipe network is not fully represented, which may affect the spatial distribution and magnitude of simulated flood depths. The network reduction assumes a uniform drainage capacity across all impervious surfaces, whereas in reality the connectivity between surface runoff and the pipe network varies. Areas with poor connectivity to the drainage network may therefore be less accurately represented than areas with well-functioning drainage infrastructure. In addition, there's an uncertainty regarding how subsidence influences the pipe network and its function.

The resolution of the subsidence data represents a further limitation. While the hydrodynamic model operates at 1x1 m grid resolution, the subsidence data was only available at a 5x5 m resolution. To incorporate it into the model, each 5x5 m subsidence value was projected onto the underlying 1x1 m grid, assuming uniform subsidence within each cell. This downscaling approach introduces uncertainty, particularly given that the results indicate that even small topographic changes over short distances can influence flood outcomes. In addition, the subsidence data was only available for the case study area, meaning that the rest of the hydrodynamic model area uses current terrain in both Scenario A and Scenario B. Introducing a subsidence adjusted terrain to the entire hydrodynamic model area would alter the flow paths of water outside of the case study area and potentially affect the volume of water reaching the case study area in Scenario B and therefore affect the comparison. Further on, the choice of climate factor influences the absolute magnitude of simulated flood depths, and consequently, which areas exceed critical thresholds such as the 20 cm limit on prioritised roads.

Although some of these limitations introduce uncertainty in the absolute flood depths simulated, all are consistent in both scenarios. Since the study is fundamentally a comparative analysis, systematic simplifications that apply consistently across both models do not invalidate the relative differences observed. This is a key reason why the results can be considered credible despite the model constraints. However, it should be noted that shared limitations do not guarantee that the comparison is entirely unaffected. A simplification that is identical in both models may still interact differently with two terrains and produce asymmetric effects on the results. For instance, the treatment of enclosed courtyards illustrates this point: while water is prevented from draining onto streets in both scenarios, the redistribution of water, and its influence on flood pathways and depths may vary between the scenarios. It is therefore possible that allowing water to exit courtyards realistically would either amplify or reduce the differences observed between the scenarios, and this uncertainty cannot be fully resolved without a more detailed representation of urban structures.

6.4 Implications for urban flood planning

The findings of this study have direct relevance to urban flood risk planning and the long-term effectiveness of pluvial flood mitigation. The structural plans and action programmes developed by the City of Gothenburg to address cloudburst risk

have been designed based on current topographic conditions, without accounting for the gradual changes in surface gradients and local depressions that subsidence may introduce over time. This study suggests that such plans may therefore be based on an incomplete picture of future flood risk.

The results show that several areas already identified as flood-prone under current conditions expand in extent or exhibit increased water depths under the subsidence scenario, while other show reduced exposure. Where mitigation measures have already been planned or implemented, this raises the risk of under- or over-dimensioning relative to future conditions, and in areas not yet on the planning radar, subsidence may give rise to flood problems that current assessments would not anticipate. In both cases, there is a risk that public investment in flood infrastructure does not deliver its intended value over its full service life, representing a misallocation of resources that could have been avoided with a better understanding of the impact of long-term ground movement on flood effects.

It should be emphasised that current design practice is not necessarily wrong. The changes identified in this study are projected over a 100-year horizon, and measures being implemented today are perhaps not expected to account for conditions that far into the future. The concern arises primarily when long-lived physical infrastructure, such as permanent drainage systems, underground structures, or large-scale surface remodelling, is designed without consideration of how the surrounding terrain may evolve. For such investments, even modest long-term changes in surface topography due to subsidence could affect whether the intended function is maintained over the structure's service life. The findings of this study do not suggest that the changes are dramatic, but they indicate that they are present, and that they are systematic enough to warrant consideration in long-term urban flood resilience planning.

6.5 Future work

The compounding risk of subsidence and pluvial flooding warrants further investigation, and several directions for future research can be identified based on the findings of this study.

First, a more applied approach would be to evaluate the performance of planned flood mitigation measures under a subsidence-adjusted scenario. While this study has discussed the risk of existing plans representing a misallocation of resources, this cannot be confirmed without assessing how specific measures perform under future ground conditions. Such an analysis would provide a more concrete understanding of the societal implications of the combined risk of subsidence and pluvial flooding.

Second, this study has been conducted in a single urban area with particular soil conditions, topography, and development characteristics. Replicating both approaches in areas with different characteristics would allow for broader conclusions regarding if and how subsidence should be incorporated into pluvial flood assessments. In this regard, it would be valuable to apply the methodology to a greenfield development area, where decisions about the placement of stormwater infrastructure have not yet been made. In such a context, accounting for subsidence from the outset could meaningfully influence both the delineation of risk areas and the design and placement of mitigation measures.

Third, future work should aim to address the limitations identified in this study

by including higher resolution subsidence data and developing a more complete representation of hydrological structures. This includes coupling the surface model to a detailed 1D pipe network and a river network model, as well as improving the representation of urban structures. A more realistic model would strengthen the ability to connect simulation results to real-world planning decisions, such as evaluating the performance of proposed flood mitigation measures or assessing compliance with design standards under future ground conditions.

Overall, the suggestions for future research share a common goal: to inform how municipalities can integrate long-term ground movement into cloudburst planning and to develop more transferable guidelines for practitioners. While this study offers valuable insights and quantitative results for a specific area in Gothenburg, the ultimate aim is for this knowledge to be translated into practical guidance that can be applied more broadly in urban flood resilience planning.

7. Conclusion

This thesis investigated the impact of long-term ground subsidence on pluvial flood analysis by comparing two detailed hydrodynamic models in MIKE+, one representing current terrain and one incorporating subsidence-adjusted terrain projected 100 years into the future. In parallel, a simplified risk assessment was evaluated as a potential first-stage screening tool.

The MIKE+ modelling demonstrates that subsidence influences the spatial distribution of flooding, water depths, and flow paths in ways that current planning practice does not account for. While existing flood-prone areas generally expand and deepen, some areas show reduced flood exposure. This bidirectional response has direct implications for planning. Where flood conditions worsen, existing mitigation measures may prove insufficient, while where they improve, measures may be over-dimensioned relative to future conditions. The relationship between subsidence and flood response is non-linear and complex. Equal magnitudes of subsidence can produce markedly different outcomes depending on local topography and the spatial variability of ground movement. Low-lying areas underlain by deep clay deposits and subject to spatially variable subsidence consistently coincide with the most pronounced changes in flood behaviour. However, this relationship is not reversible. The presence of these conditions does not guarantee altered flood outcomes, but where significant changes do occur, these conditions are invariably present.

The simplified risk assessment showed partial spatial correspondence with the MIKE+ results, confirming its potential as a first-stage screening tool. However, subsidence magnitude alone proved an insufficient screening criterion. A more reliable assessment should examine the coincidence of low-lying terrain or local depressions, deep clay deposits, and spatially variable subsidence, and apply a spatial buffer around identified zones. This approach would serve as a useful first-stage indicator of areas potentially subject to subsidence-induced changes in flood behaviour.

Collectively, the findings demonstrate that long-term ground subsidence is a relevant but currently overlooked factor in urban pluvial flood planning, and that integrating it into hydrodynamic models produces meaningful differences in simulated flood outcomes.

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Appendix 1 – Rainfall data

This appendix presents rainfall data expressed in mm/h for each respective timestamp. Rainfall on pervious surface represents the entire calculated CDS rain while rainfall on impervious surfaces includes a drainage network deduction corresponding to the rainfall volume equivalent to a 10-year return period event.

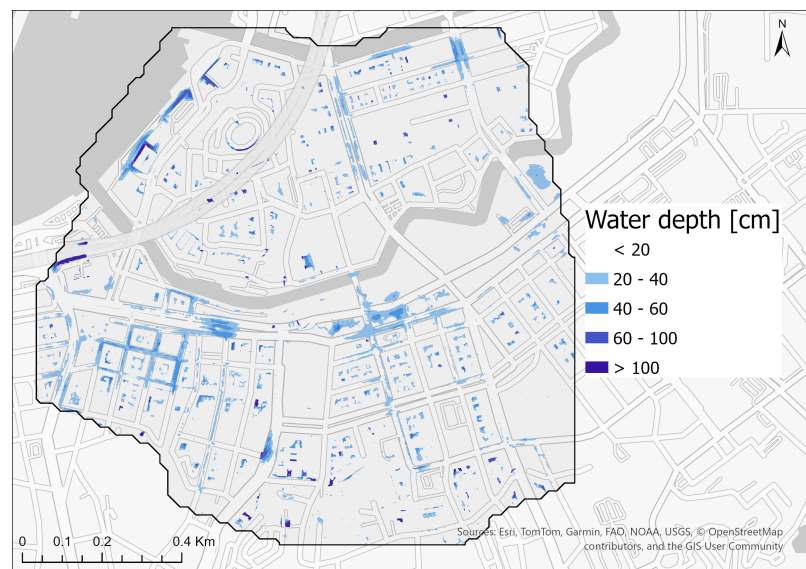
Timestamp	Rainfall on pervious surfaces [mm/h]	Rainfall on impervious surfaces [mm/h]
2026-07-01 15:00:00	0.00	0.00
2026-07-01 15:05:33	3.93	0.00
2026-07-01 15:11:06	4.1	0.00
2026-07-01 15:16:39	4.28	0.00
2026-07-01 15:22:12	4.43	0.00
2026-07-01 15:27:45	4.68	0.00
2026-07-01 15:33:18	4.91	0.00
2026-07-01 15:38:51	5.16	0.00
2026-07-01 15:44:24	5.43	0.00
2026-07-01 15:49:57	5.74	0.00
2026-07-01 15:55:30	6.08	0.00
2026-07-01 16:01:03	6.46	0.00
2026-07-01 16:06:36	6.86	0.00
2026-07-01 16:12:09	7.39	0.46
2026-07-01 16:17:42	7.96	1.03
2026-07-01 16:23:15	8.64	1.71
2026-07-01 16:28:48	9.44	2.51
2026-07-01 16:34:21	10.38	3.45
2026-07-01 16:39:54	11.76	4.83
2026-07-01 16:45:27	13.31	6.38
2026-07-01 16:51:00	15.53	8.60
2026-07-01 16:56:33	18.09	11.16
2026-07-01 17:02:06	17.69	10.76
2026-07-01 17:07:39	20.3	13.37
2026-07-01 17:22:39	196.82	189.89
2026-07-01 17:32:06	20.3	13.37
2026-07-01 17:41:33	17.69	10.76
2026-07-01 17:51:00	18.09	11.16
2026-07-01 18:00:27	15.53	8.60
2026-07-01 18:09:54	13.31	6.38
2026-07-01 18:19:21	11.76	4.83
2026-07-01 18:28:48	10.38	3.45
2026-07-01 18:38:15	9.44	2.51
2026-07-01 18:47:42	8.64	1.71
2026-07-01 18:57:09	7.96	1.03

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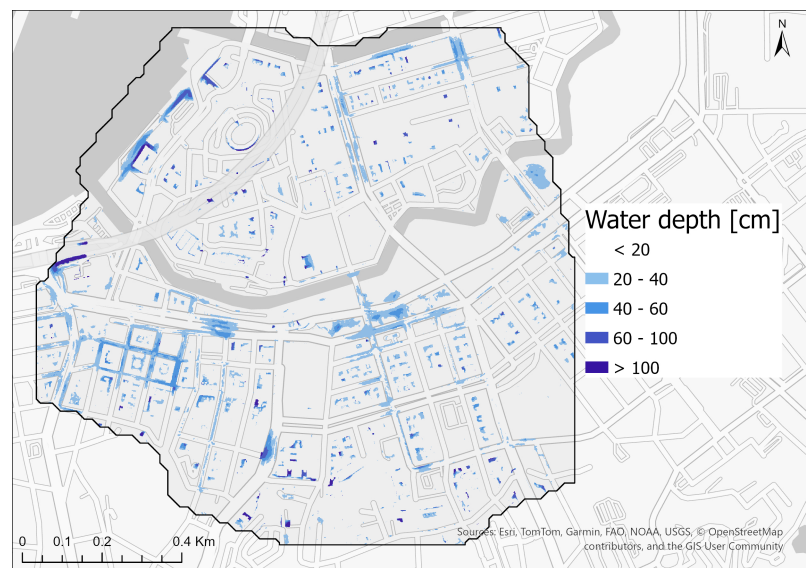
Timestamp	Rainfall on pervious surfaces [mm/h]	Rainfall on impervious surfaces [mm/h]
2026-07-01 19:06:36	7.39	0.46
2026-07-01 19:16:03	6.86	0.00
2026-07-01 19:25:30	6.46	0.00
2026-07-01 19:34:57	6.08	0.00
2026-07-01 19:44:24	5.74	0.00
2026-07-01 19:53:51	5.43	0.00
2026-07-01 20:03:18	5.16	0.00
2026-07-01 20:12:45	4.91	0.00
2026-07-01 20:22:12	4.68	0.00
2026-07-01 20:31:39	4.43	0.00
2026-07-01 20:41:06	4.28	0.00
2026-07-01 20:50:33	4.1	0.00
2026-07-01 21:00:00	3.93	0.00
2026-07-02 01:00:00	0.00	0.00

Appendix 2 – Water depth from MIKE+ simulations

This appendix presents water depth results from the MIKE+ simulations for Scenario A and Scenario B. Only water depths of 20 cm and above are visualised on the map.



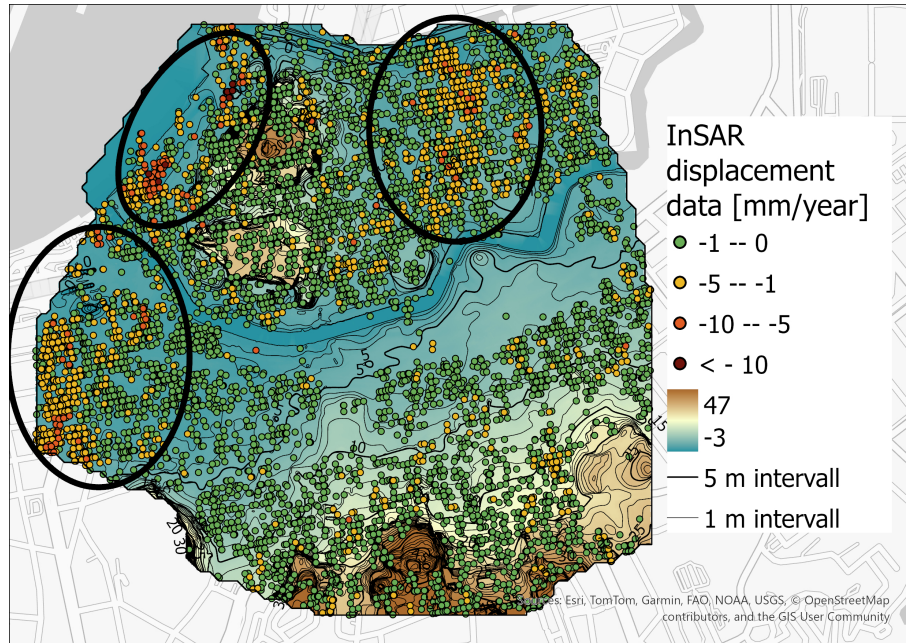
Maximum water depth in Scenario A.



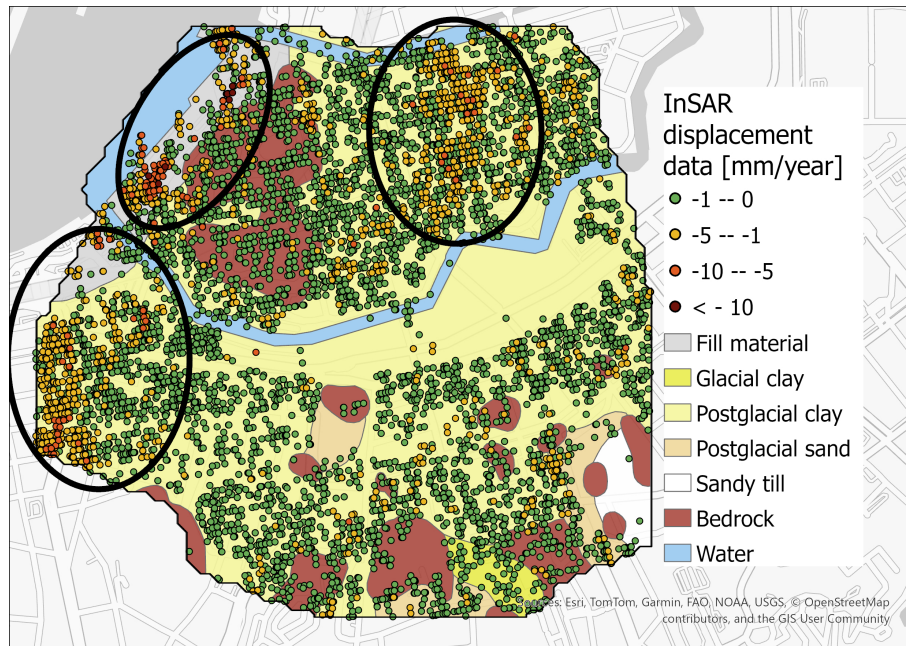
Maximum water depth in Scenario B.

Appendix 3 – Overlay maps from simplified risk assessment

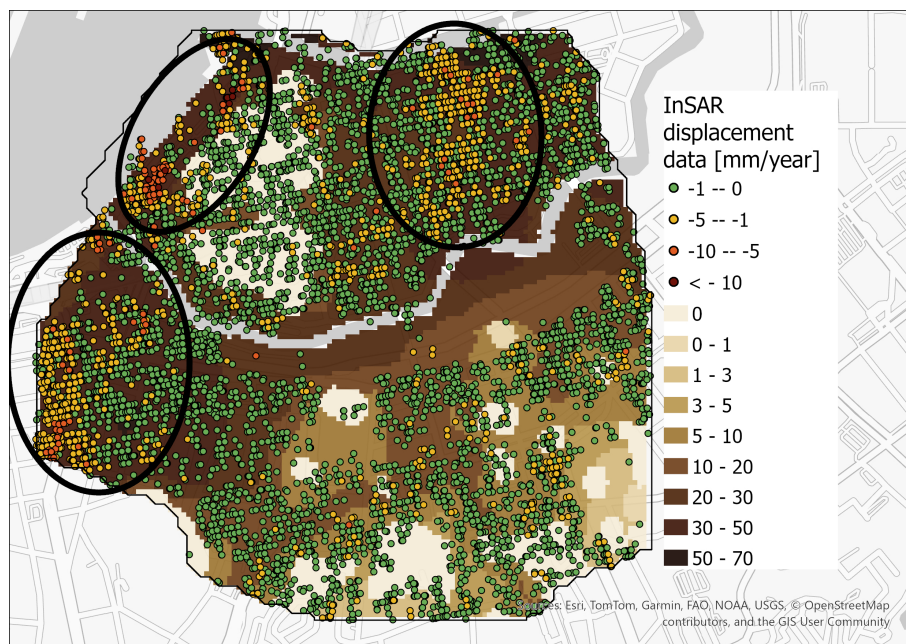
This appendix presents maps over the case study area illustrating InSAR displacement data underlain by topography, soil categorisation, and soil depth respectively.



Merged layer of InSAR subsidence data (Swedish Geotechnical Institute, 2026a) and topography data (Scalgo, n.d.a).



Merged layer of InSAR subsidence data (Swedish Geotechnical Institute, 2026a) and soil categorisation (Geological Survey of Sweden, 2026a).



Merged layer of InSAR subsidence data (Swedish Geotechnical Institute, 2026a) and soil depth (Geological Survey of Sweden, 2023).

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