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Hydraulic Modelling of Flood Impact in a Regulated Urban River

A case study of Mölndalsån in
Gothenburg

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Division of Water Resources Engineering
Department of Building and Environmental Technology
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Abstract

Urban flooding is an increasing challenge in Gothenburg, where flood risk is influenced by river discharge, elevated sea levels and hydraulic regulation. The river Mölndalsån contributes to this risk as it flows through urban areas before discharging into Göta älv. Future climate change may further increase the risk through rising sea levels and more intense precipitation.

This thesis investigates flood risk in Mölndalsån using a one dimensional hydraulic model. The study focuses on how water levels respond to different combinations of river inflow, downstream sea level and regulation by hydraulic structures. An existing MIKE+ Rivers model was modified to represent the regulating structures at Gårda dämme and Slussen, and calibration and validation were performed using historical data. Three river inflow scenarios and three sea level scenarios were combined into nine steady state simulations. Simulated water levels were evaluated at eight selected critical locations and compared with local bank levels. In addition, the temporary storage capacity of the river system was analysed by closing the regulating structures and allowing the system to fill from a lowered initial level.

The results showed that flood risk varies along the river system and is strongly influenced by hydraulic regulation. The upstream and central parts of Mölndalsån were primarily affected by river inflow, while the most downstream parts were predominantly controlled by sea level, and some locations were influenced by both factors. Several critical locations exceeded their bank levels in the simulated scenarios, and one location close to Gårda fire station was identified as particularly vulnerable.

The study concludes that flood mitigation in Mölndalsån should be adapted to the dominant flood factor in each part of the system. The storage analysis showed that temporary closure of the regulating structures could provide flood mitigation during high sea level events, especially under low inflow conditions. Coordinated regulation of upstream and downstream structures is therefore important for reducing future flood risk.

Table of content

Table of Contents	VI
1 Introduction	1
1.1 Background	1
1.2 Objectives	2
1.3 Research approach	2
1.4 Limitations	3
2 Flood risk in Gothenburg and along Mölndalsån	5
2.1 Urban flood risk	5
2.2 Flood risk in Gothenburg	5
2.3 The 2006 flood event	6
2.4 Flood mitigation measures after 2006	6
2.5 Recent flooding events	7
2.6 Future flood risk under climate change	7
3 Study area – Mölndalsån	9
3.1 Study area overview	9
3.2 Hydrology and catchment characteristics	14
3.3 Current sea conditions	15
3.4 Existing flow regulation and water permit	16
3.5 Existing hydraulic structures	16
3.5.1 Gårda dämme	17
3.5.2 Slussen	19
3.5.3 System operation	22
3.5.4 Future plans	22
3.6 Previous research in the study area	23
3.6.1 Temporary storage	25
3.7 Previous research on flow regulation	26
4 Theoretical Background	27
4.1 Hydrodynamics – Shallow water equations	27
4.2 Coastal processes	28
4.2.1 Extreme water levels	28
4.2.2 Sea level rise	29
4.3 Compound flooding	30
4.4 Flow regulation	30
4.5 Risk and return periods	31
5 Data employed and analysis	33

5.1	Sea level data	33
5.2	River flow	37
5.3	Final scenarios	40
6	Model setup and implementation	43
6.1	The MIKE+ rivers model	43
6.2	Regulating structures	47
6.3	Selection of critical locations	47
6.4	Model calibration and validation	48
6.5	Water level simulations	49
6.6	Temporary storage capacity	49
7	Results and discussion	51
7.1	Critical locations	51
7.2	Calibration and validation	57
7.3	Water level simulations	59
7.3.1	Locations A and B	61
7.3.2	Locations C and D	61
7.3.3	Locations E and F	62
7.3.4	Locations G and H	62
7.4	Temporary storage capacity	63
7.4.1	Storage with existing regulating structures	63
7.4.2	Storage with additional regulating structures	64
7.4.3	Comparison with previous research	65
7.4.4	Comparison between storm durations and maximum closure times	66
7.5	Recommendations for flood mitigation	67
7.5.1	Mitigation by river section	67
7.5.2	Utilising the temporary storage	68
8	General discussion	69
8.1	Uncertainties	69
8.2	Future work	70
9	Conclusions	71
	Bibliography	73

1 Introduction

This chapter introduces the background and purpose of the thesis, followed by the research questions, overall approach and limitations. Moreover, it presents the flood risk context in Gothenburg and Mölndalsån.

1.1 Background

Flooding in urban areas poses a significant threat to society, infrastructure and public services. Cities are often densely populated and contain extensive critical infrastructure, which means that flooding can have consequences that extend beyond immediate physical damage. Transport networks may be disrupted, buildings may be damaged, and environmental and health risks may arise. The consequences may be particularly severe in low lying areas where drainage is limited and water can remain for an extended period [1].

Gothenburg is particularly vulnerable to flooding due to its coastal location, low elevation and the presence of several watercourses running through the city. Flood risk can arise from high river discharge, elevated sea levels, intense rainfall, or a combination of these processes. One of the water systems that contributes to the flood risk is the river Mölndalsån, which flows through urban areas before discharging into the river Göta älv [1].

The vulnerability of the system became clear during the 2006 flood, when rainfall and high river discharge, from previous rainfall events, contributed to major flooding in several parts of Gothenburg. The event caused damage to buildings, roads and public services, and led to increased focus on coordinated regulation and flood mitigation measures along Mölndalsån [2]. However, flooding related to Mölndalsån has continued to occur, indicating that flood risk remains an important issue for the city [3]. Additionally, future climate change may further increase flood risk through rising sea levels and more intense precipitation events [4]. When high sea levels and high river discharge occur simultaneously, the resulting compound flooding can be particularly challenging to manage.

This highlights the need to evaluate how Mölndalsån responds to different combinations of sea level and river inflow, and how the existing regulating structures influence water levels during flood conditions.

1.2 Objectives

The aim of this thesis is to investigate flood risk in Mölndalsån using hydraulic modelling. The study focuses on how water levels in the river system respond to variations in river inflow, sea level and regulation by hydraulic structures. The study identifies hydraulic conditions and locations associated with increased flood impact, and provides a basis for discussing possible flood mitigation strategies in the study area.

This will be addressed through answering the following questions:

- How does Mölndalsån respond to different combinations of river inflow and sea level?
- Where along the river system may flooding occur under the selected hydraulic scenarios?
- How can existing and potential regulation strategies contribute to flood mitigation?

1.3 Research approach

This study was carried out through a combination of literature review, field observations, data analysis and hydraulic modelling. These steps were used to develop an understanding of the river system, define relevant model scenarios and evaluate how water levels in Mölndalsån respond to different combinations of sea level and river inflow.

Previous studies, reports, maps and the current water permit were reviewed to understand the study area, previous flood events and the existing regulating structures. Literature concerning hydraulic modelling, flood risk and compound flooding was also reviewed to provide a theoretical basis for the study. Particular focus was placed on the regulating structures at Gårda dämme and Slussen, since these have a major influence on the hydraulic behaviour of the system.

A field visit was conducted to gain a better understanding of the river system and its surroundings. Selected parts of the river were inspected, including riverbanks, nearby land use and hydraulic structures. Observations and photographs from the field visit were used to support the interpretation of the existing model and to identify locations that may be vulnerable to flooding.

Historical sea level and river flow data were analysed to define representative boundary conditions for the hydraulic model. Based on this analysis, sea level and river flow scenarios were developed and later combined in the simulations. The simulated water levels were then evaluated at selected critical locations along the river in order to assess where flooding may occur under different hydraulic conditions.

1.4 Limitations

The study involves the following limitations:

- Rainfall and stormwater runoff entering the river within the urban area are not included. The analysis only considers the defined upstream inflows to the modelled river system.
- Flooding is defined as overtopping of the river banks. A simplified representation of flow paths on urban surfaces is included in the model, but flow is only calculated in one direction along the river. Flood paths perpendicular to the river cannot be described, and overland structures such as buildings are not included.
- The simulations are based on selected representative steady state scenarios rather than historical events.
- The river channel is assumed to be free from debris, vegetation blockage, branches or other objects that could obstruct the flow.
- Existing hydraulic structures are assumed to remain functional and maintain their original hydraulic capacity during the simulations. Structural damage, blockage or failure is not considered.
- The regulating structures at Gårda dämme and Slussen are represented in the hydraulic model, but some details of their operation are generalised.
- Waves from the sea are neglected, including wind induced waves and standing waves.

2 Flood risk in Gothenburg and along Mölndalsån

This section presents the background relevant to flood risk in Gothenburg and Mölndalsån. It describes the impacts of urban flooding, the local conditions that make Gothenburg vulnerable, historical flood events, and implemented mitigation measures. Finally, future flood impact and mitigation measures related to climate change are discussed.

2.1 Urban flood risk

Urban flooding can affect cities in several ways. Beyond direct damage to buildings and infrastructure, flood events may disrupt essential services, transport systems and emergency response. If healthcare facilities or emergency services are affected, the ability to respond to emergencies may be reduced, which can put human lives at risk. Flooded roads and transport networks may also limit mobility within and to the city, which can interrupt the transport of goods and lead to economic losses or shortages of essential supplies [1].

Flood events can also create environmental and health risks. Floodwaters may spread pollutants from contaminated land, which can affect surrounding ecosystems and impact sources of drinking water. In addition, wastewater collection and treatment may be disrupted, which can further threaten environmental quality and public health [1].

Another challenge associated with flooding is that accumulated water may remain in low-lying areas for a long time, particularly where drainage by gravitational flow is limited. This can prolong the impacts and increase the damage. Flood events may also destabilize slopes and increase the risk of landslides [1].

2.2 Flood risk in Gothenburg

The potential consequences of flooding in Gothenburg are significant, as the city is Sweden's second largest city and has a large population, extensive critical infrastructure, public services, and ecologically important areas that support local plant and animal life. This includes major roads, national railway lines, hospitals, schools, fire stations and industrial areas [1].

A report focusing on Mölndalsån concluded that a flow corresponding to a 50 year return period would flood a fire station, a contaminated area, cultural heritage and two schools. A 100 year return period flow would additionally affect another school, major roads and railways, as well as the collection and treatment of wastewater [5].

A second report, which investigated flood impacts across the whole city of Gothenburg rather than only Mölndalsån, found that an extreme flood event could affect approximately 3 400 residents, 1 500 workplaces, 21 500 employees, in addition to several public services. The analysed event represented a worst case scenario in which snowmelt, precipitation and elevated water levels occurred simultaneously [1].

2.3 The 2006 flood event

In December 2006, Gothenburg experienced one of its most severe floods in the past 30 years. The autumn and winter that year were particularly rainy, which led to elevated river levels. When additional heavy rainfall occurred while river levels were already high, major flooding developed in several parts of the city [2].

The river discharge during the event corresponded to a return period of up to 50 years. The flood damaged multiple buildings and roads, affecting both private individuals and public services [2], including a hospital and a fire station [6].

2.4 Flood mitigation measures after 2006

At the time of the 2006 flood, there was no coordinated regulation of flow in Mölndalsån, meaning all five regulating structures along the river had different owners and were operated according to separate rules. Following the flood, a collaboration was established between the three municipalities through which Mölndalsån flows, that is Gothenburg, Mölndal and Hälaryda [7].

The aim of the collaboration was to reduce the risk of both floods and droughts in a sustainable and cost efficient way. This was achieved through the development of a coordinated control strategy and updated water regulations, together with a technical approach that included analysis of historical and present flows as well as forecasts of flow conditions [7].

Other measures implemented after the 2006 flood included dredging and removal of vegetation, replacement of the existing gate structures at Slussen, reconstruction of the gate at Gårda dämme, and in some locations widening and deepening of the river channel to increase the hydraulic capacity.

The current regulation strategy aims to even out the flow by releasing water from the downstream lakes Stensjön and Rådasjön when heavy rainfall or high sea levels are forecast, thereby increasing the available water storage capacity in the lakes [7].

2.5 Recent flooding events

Despite the mitigation measures implemented after the 2006 flood, flood events related to Mölndalsån have continued to occur with varying severity. Flooding of Mölndalsån was reported again in 2008, followed by a flash flood in 2010 [8]. Heavy rainfall in 2011 caused flooding that disrupted infrastructure throughout the city and resulted in one person being critically injured [3].

2.6 Future flood risk under climate change

Climate change is expected to contribute to rising sea levels and more intense precipitation, which may increase river discharge. As a result, flood risk in Gothenburg is likely to increase. When high sea levels and high river discharge occur simultaneously, the situation is often referred to as compound flooding, which is a complex challenge for flood management [4].

To address these challenges, the municipality of Gothenburg has initiated a flood protection program called Högvattenskyddsprogrammet. The program focuses on protecting people, buildings, infrastructure, cultural assets, and public services. The aim is to ensure long term safety and sustainability through planning, cooperation, and the implementation of protective measures along waterways, such as flood barriers, raised ground levels and pump stations [4].

The city of Gothenburg has also entered into a collaboration with several European cities and universities through the EU funded Interreg project STORM SAFE. The purpose of the project is to increase resilience to future high water events by developing and applying software for water flow management. Participating countries include Sweden, Denmark, Germany and the Netherlands, together with the universities of Lund, Twente, Aalborg and Eindhoven. Through this collaboration, knowledge and experience are shared to improve flood protection across the North Sea region [6]. Within the Stormsafe project, Mölndalsån has been selected as a case study for investigating the effectiveness and operation of flood gates in an urban river system affected by compound flooding.

3 Study area – Mölndalsån

This section describes the Mölndalsån river system, including its catchment characteristics, sea level influence, existing flow regulation and hydraulic structures. Previously identified flood risks and examples of similar flow regulation systems are also presented.

3.1 Study area overview

The river system originates from a small spring in the forest near the village of Hindås. From there, the water flows through the five lakes Östra Nedsjön, Västra Nedsjön, Landvettersjön, Rådasjön and Stensjön, before continuing downstream and joining Källeredsbäcken in Mölndal. Downstream of this point, the river is referred to as Mölndalsån [7]. Downstream of Mölndal, the river flows for around 11 km in an open channel consisting of both natural sections and sections with hard structures, including a few short culverts [9]. Figure 3.1 shows the upstream lakes and dams, and Figure 3.2 shows the downstream part of Mölndalsån.

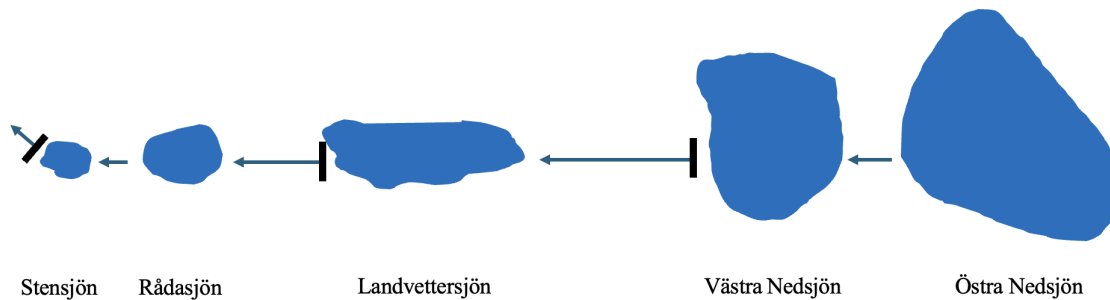


Figure 3.1: Schematic illustration of the upstream lakes, in blue, and dams, as black rectangles.

At Gårda dämme, Mölndalsån divides into the two branches Gullbergsån and Fattighusån. Gullbergsån is about 2 km long and starts by passing through the gates at Gårda dämme. Thereafter, it runs through an open section before entering a 500 m long culvert beneath a major railway and motorway embankment, shown in Figure 3.3 and Figure 3.4. It then connects to Säveån, which shortly afterwards discharges into Göta älv [9].

Fattighusån is a man made canal roughly 3 km long that flows through central Gothenburg [9]. After passing the gates at Slussen, the canal further divides into the branches Stora Hamnkanalen and Rosenlunds kanal, both of which discharge into Göta älv. Göta älv in turn discharges into the Kattegatt sea [7]. Fattighusån, Stora Hamnkanalen and Rosenlunds kanal are shown in Figure 3.5, 3.6 and 3.7 respectively.

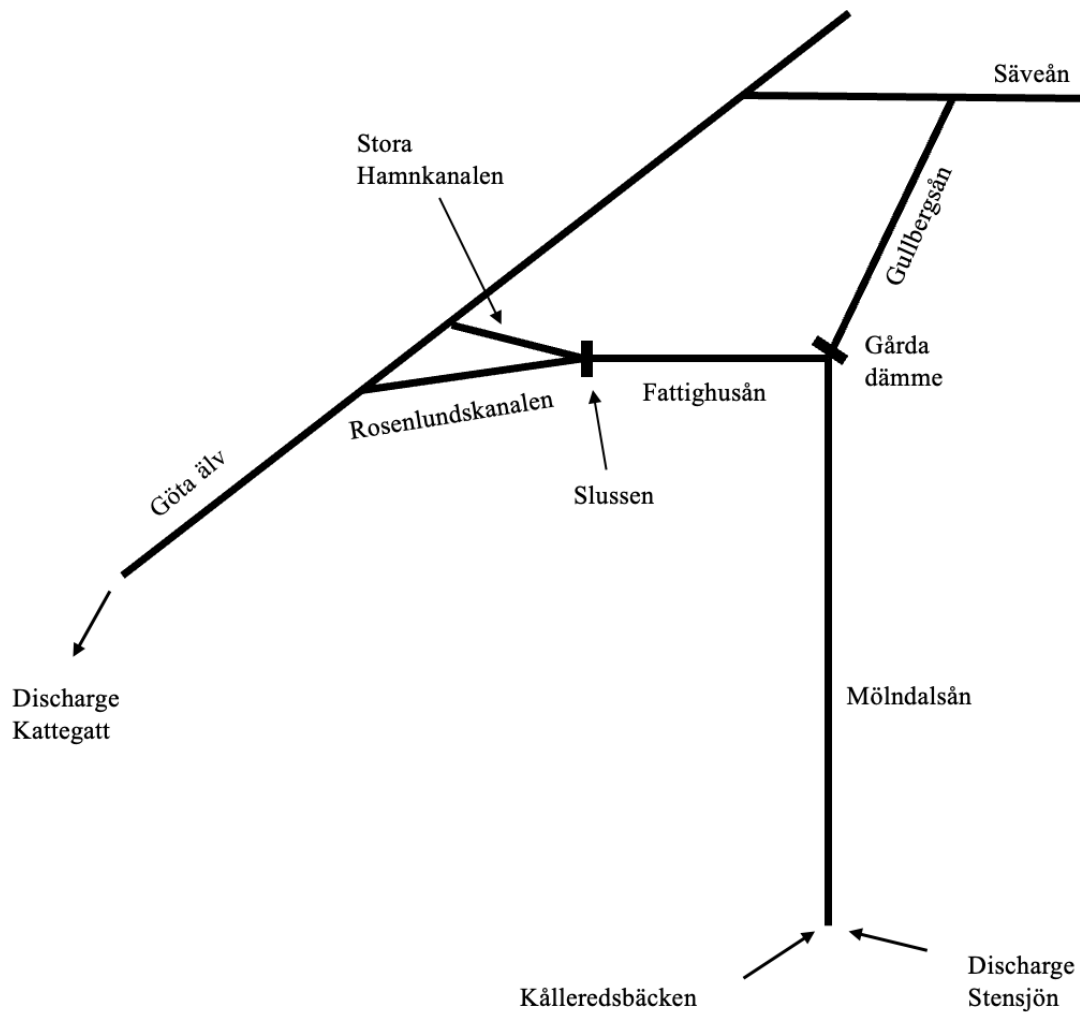


Figure 3.2: Schematic illustration of the downstream part of Mölndalsån including the existing structures.

From its source to its outlet in Göta älv, the water travels approximately 45 kilometers and falls around 120 m in elevation. The surrounding landscape is varied and of high recreational and ecological value. Mölndalsån passes through 11 nature reserves and supports a diverse range of terrestrial and aquatic species. Variations in flow conditions along the river create a range of habitats and contribute to a high biological diversity, including species such as salmon, trout and eel. In addition, the river system is an important source of drinking water [7].



Figure 3.3: Photograph of Gullbergsån. By Vera Åkerlund



Figure 3.4: Photograph of the inlet to the Gullbergsån culverts. By Vera Åkerlund.



Figure 3.5: Photograph of Fattighusån. By Vera Åkerlund



Figure 3.6: Photograph of Stora Hamnkanalen. By Vera Åkerlund.



Figure 3.7: Photograph of Rosenlundskanalen. By Vera Åkerlund

3.2 Hydrology and catchment characteristics

According to the SMHI model SHYPE, the catchment area of Mölndalsån is 265 km² and consists primarily of forest (47%) , urban areas (22%), lakes and rivers (11%). Agricultural land and other land uses together account for the remaining 20%. The entire catchment area is shown in Figure 3.8. The mean annual precipitation for the period 1991-2020 is approximately 1 100 mm/year [10].

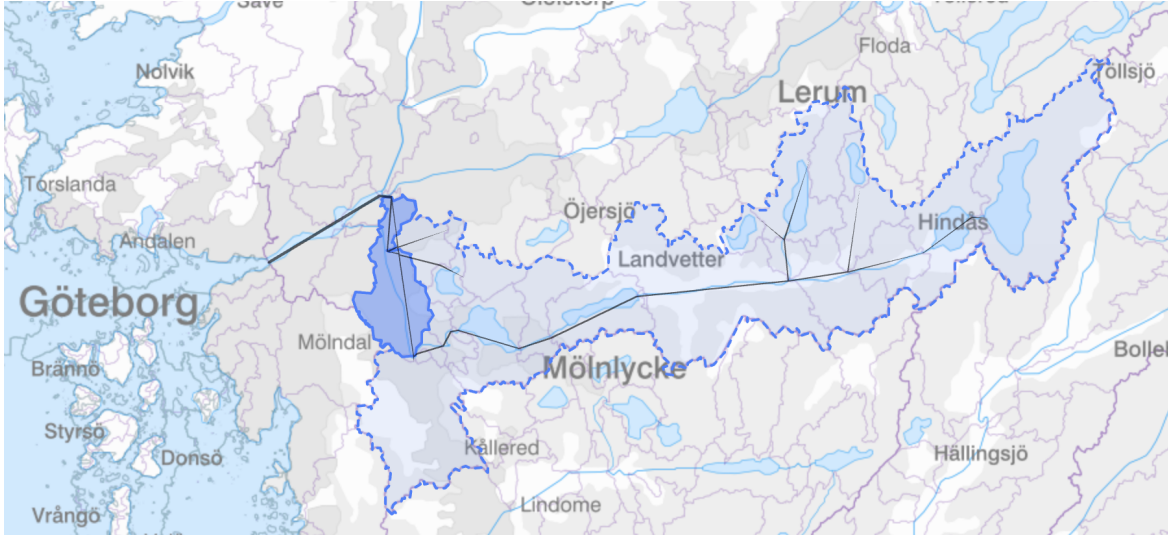


Figure 3.8: The catchment area of Mölndalsån from S-HYPE [10]. The light blue area shows the total catchment while the darker blue shows a subcatchment close to downstream Mölndalsån.

Discharge statistics from the SMHI S-HYPE model for the same period are presented in Table 3.1. These values represent the estimated natural flow conditions in Mölndalsån, that is, the discharge that would occur in the absence of flow regulation. Although these values cannot be applied directly in this study because the river is regulated, they provide an indication of the magnitude and return periods of different flow conditions. The flows are presented in terms of return periods, which describe how often a certain event is expected to occur on average.

Table 3.1: Discharge statistics for Mölndalsån from S-HYPE [10].

Definition	Flow [m ³ /s]	Description
HQ50	32.3	50 year return period
HQ25	30.0	25 year return period
HQ10	26.8	10 year return period
HQ5	24.3	5 year return period
HQ2	20.5	2 year return period
MHQ	21.2	Mean of the highest flows
MQ	5.34	Mean flow
MLQ	0.529	Mean of the lowest flows

Mölndalsån flows from east to west and is joined by Källeredsbäcken, which flows from south to north, in the town of Mölndal. The catchment area of Mölndalsån therefore includes that of Källeredsbäcken. However, discharge statistics for Källeredsbäcken are presented separately in Table 3.2, since its flow is not regulated. These statistics were also collected from the SMHI model SHYPE [10].

Table 3.2: Discharge statistics for Källeredsbäcken from S-HYPE [10].

Definition	Flow [m ³ /s]	Description
HQ50	4.93	50 year return period
HQ25	4.56	25 year return period
HQ10	4.07	10 year return period
HQ5	3.68	5 year return period
HQ2	3.09	2 year return period
MHQ	3.2	Mean of the highest flows
MQ	0.5	Mean flow
MLQ	0.012	Mean of the lowest flows

3.3 Current sea conditions

Since Mölndalsån discharges into Göta älv and further into Kattegatt, elevated sea levels can propagate upstream and influence water levels in the downstream parts of the river system, particularly near Slussen and Gårda dämme. During storms, strong westerly winds may push water from the Atlantic Ocean into Kattegatt, leading to temporarily elevated water levels along the Gothenburg coast [11].

A report by Sweco estimated return periods for different sea levels in 2014 at two locations. The first location was Torshamnen, located outside Gothenburg towards the sea, where the values were based on measurements from a sea level station. The second location was where Gullbergsån discharges into Säveån and Göta älv, representing a location closer to the city centre. The values for the second location were based on interpolation from Torshamnen. The results are presented in Table 3.3. According to the report, water levels may differ 10-30 cm between the two locations during storm conditions [12].

Table 3.3: Return period of sea levels in Torshamnen and the discharge point of Gullbergsån relative RH2000 [12].

Return period	Sea level Torshamnen [m]	Sea level Gullbergsån outlet [m]
1	0.04	0.15
10	1.33	1.63
20	1.43	1.73
50	1.53	1.83
100	1.61	1.91
200	1.67	1.97

3.4 Existing flow regulation and water permit

The present regulation of Mölndalsån is primarily based on maintaining specified water levels throughout the system. The operation is governed by a legal water permit, which states that [7]:

- The water level in central Mölndal must not fall below +1 m (RH2000), because of the geotechnical stability of the canal walls.
- The river level in central Mölndal must not exceed +2.9 m (RH2000) due to flood risk. Discharge from the upstream lakes must therefore be regulated to remain below the river's hydraulic capacity of 27 m³/s.
- When high flows are forecast, the upstream lakes and Mölndalsån should be lowered in advance in order to increase the available storage capacity.
- The minimum discharge from Stensjön to Mölndalsån is 0.3 m³/s.

In addition, the operational target water level upstream of Gårda dämme is +1.45 m (RH2000), which also influences the operation of Slussen [13].

3.5 Existing hydraulic structures

There are five regulating structures along Mölndalsån, from the upstream lakes to the outlet. Three of these regulate the discharge from Nedre Nedsjön, Landvettersjön and Stensjön respectively. These upstream structures are not the main focus of this thesis, but they are important for understanding the overall regulation of the river system. In the downstream part of Mölndalsån, hydraulic structures are located at Gårda dämme and Slussen [7]. These structures are mainly regulated by sluice gates, although overflow across weirs also occurs.

A sluice gate regulates flow through underflow beneath a movable vertical plate. The plate can be raised or lowered in order to control the discharge. When closed, the gate is positioned at its lowest level, typically near the channel bottom, and when opened the plate is raised [14]. The resulting underflow behaves as a jet caused by the convergence of streamlines upstream of the gate. The discharge capacity depends mainly on the difference between the upstream and downstream water levels [15].

A weir instead regulates flow through overflow across the crest of the structure. Similar to a gate, a movable weir can be adjusted vertically to control the discharge, but in this case it is lowered to increase flow capacity rather than raised [16].

3.5.1 Gårda dämme

Gårda dämme is located at the point where Mölndalsån divides into Fattighusån and Gullbergsån. The original structure was built in timber in the early 1900s. In 2013, it was rebuilt in concrete in order to improve the safety and reliability of the regulation system. At the same time, a 90 metre long fish passage was constructed [17]. The fish passage includes a weir along its length, allowing water to flow into and through the passage.

Gårda dämme consists of five automatic sluice gates, each with a width of 2.8 m, a height of 1.95 m and a bottom level of -0.45 m. The gates are operated to maintain an upstream water level of 1.45 m. Each gate can be operated individually, meaning one gate can be fully opened while another is closed [13]. Gårda dämme and the fish passage can be seen in Figure 3.9– 3.12.



Figure 3.9: Photograph of Gårda dämme from the upstream part. By Vera Åkerlund.



Figure 3.10: Photograph of Gårda dämme from the downstream part. By Vera Åkerlund.



Figure 3.11: Photograph of the fish passage at Gårda dämme. By Vera Åkerlund.



Figure 3.12: Picture of the weir along the fish passage at Gårda dämme. By Vera Åkerlund.

3.5.2 Slussen

Slussen is located next to Drottningtorget in central Gothenburg. The structure consists of two separate parts located next to each other across the channel. One part is a canal lock for boat traffic, while the other is the flow regulating structure. In this study, the term “Slussen” refers only to the regulating structure. Figure 3.13, 3.14 and 3.15 shows pictures of Slussen.

The regulation structure consists of four vertical plates, of which two function as sluice gates and two as weirs. The plates functioning as sluice gate and weirs are located at the same position and partly overlap. The extent of this overlap depends on the water level and discharge. In practice, the sluice gates are used to regulate the flow, while the weirs mainly serve an aesthetic purpose by creating a small waterfall [13].

Each sluice gate has a bottom level of -2.07 m, a width of 3 m and a height of 1.2 m. The two weirs have the same dimensions but a higher bottom level of -0.27 m. In contrast to Gårda dämme, Slussen is automatically operated to maintain an upstream water level of +1.45 m at Gårda dämme [13]. Schematic illustrations of the hydraulic structures are shown in Figure 3.16 and 3.17.



Figure 3.13: Photograph of Slussen from the downstream part. By Vera Åkerlund.



Figure 3.14: Photograph of the regulating structure at Slussen. By Vera Åkerlund.



Figure 3.15: Photograph of the canal lock at Slussen. By Vera Åkerlund.

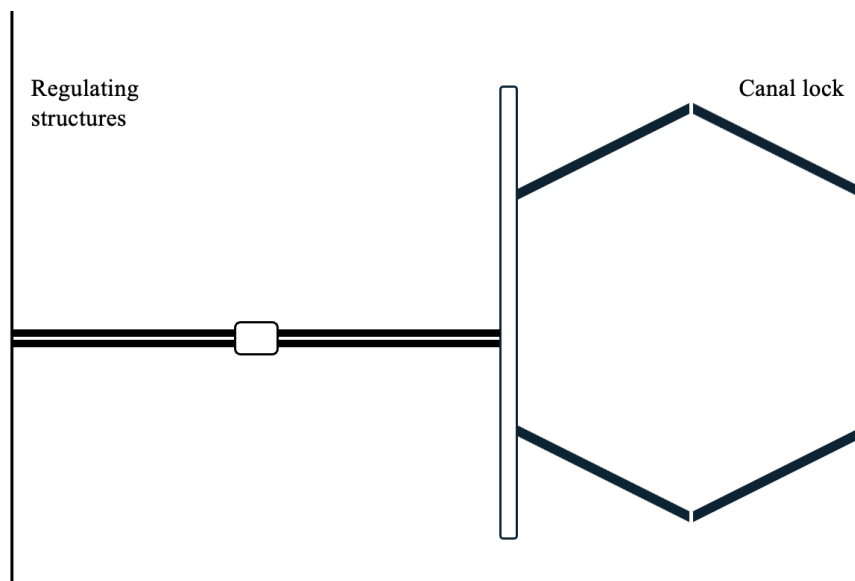


Figure 3.16: Schematic illustration of Slussen in plan view.

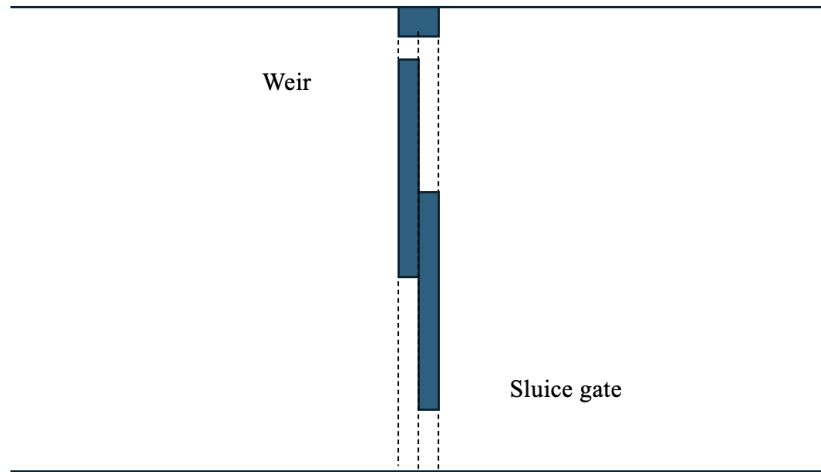


Figure 3.17: Schematic illustration of the sluice gates and weirs at Slussen.

3.5.3 System operation

Both structures operate automatically based on measurements from a water level station located upstream of Gårda dämme. The measured river level is used as input to determine whether the gates should be opened or closed further [13].

If high river flows or elevated sea levels are forecast, the system can be pre-released to an upstream water level of +1 m instead. This increases the available storage capacity within the downstream river system. Once +1 m is reached it is closed off to prevent sea level from propagating into the river system [12].

3.5.4 Future plans

There are plans to build additional hydraulic structures to protect Gothenburg against floods. One suggestion is to build inner barriers at the discharge points into Göta älv, as shown in Figure 3.18. These would protect the city centre from elevated sea levels [18]. Another suggestion is to build a large scale outer barriers in Göta älv instead, which would protect the entire city from elevated sea levels [19].

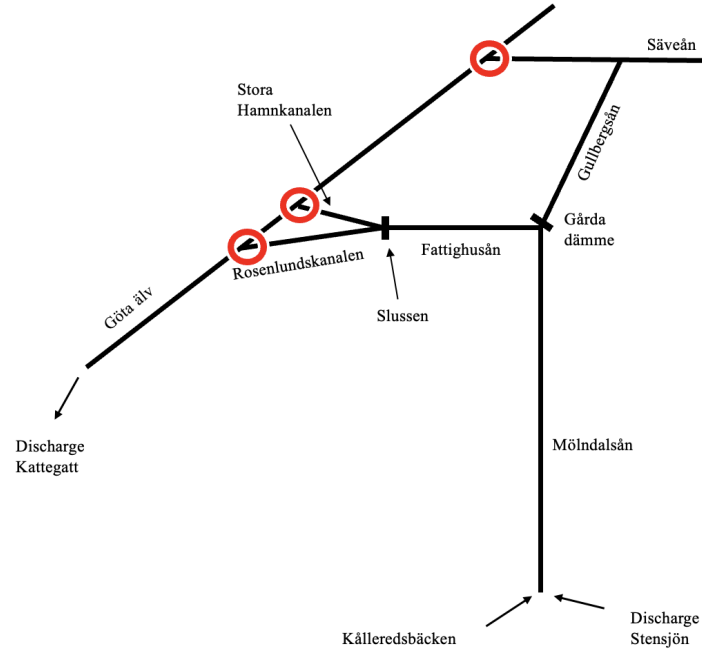


Figure 3.18: The future plans of additional inner barriers are marked in red in the schematic illustration of downstream Mölndalsån.

3.6 Previous research in the study area

The Swedish Civil Defense and Resilience Agency, MCF, has studied flooding along Mölndalsån for extreme scenarios. The analysed scenario was based on a frequency analysis of river inflow corresponding to a 100 year return period, and does not take the current water permit into account. The 100 year flow was also adjusted to represent future conditions in 2098. This resulted in a flow of $40 \text{ m}^3/\text{s}$, while the sea level was set to $+1.74 \text{ m}$ [20].

Based on this scenario, a flood impact map was produced to show infrastructure, buildings and public services that would be affected by flooding. A copy of the map is shown in Figure 3.19, while the full map is available through MCF website Översvämningsportalen. A zoomed in version of the more vulnerable locations is presented in Figure 3.20. In the map, lighter squares represent affected residents, while brown squares represent flooded buildings, the large red dot represents a fire station and the dotted area represents cultural heritage.

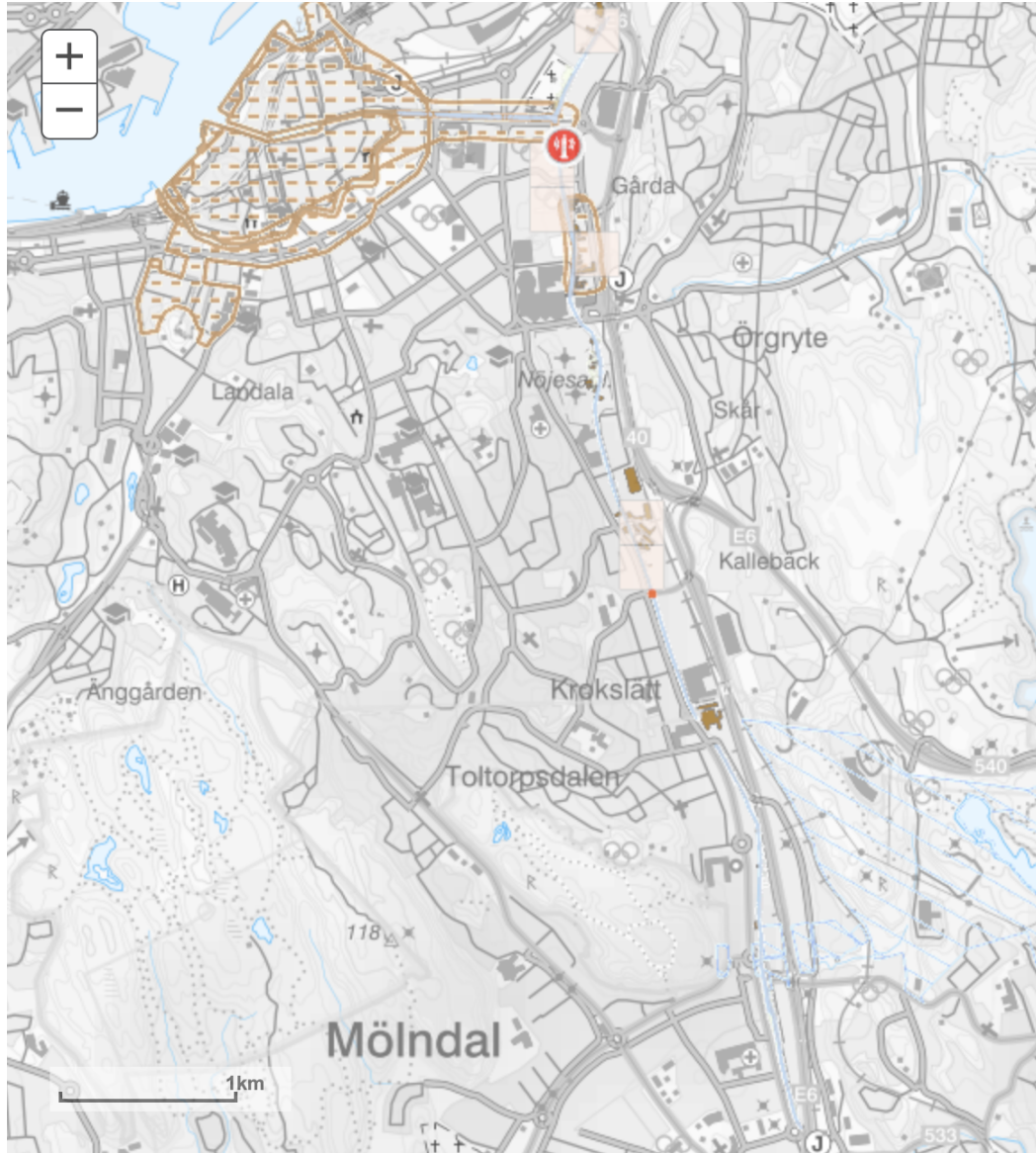


Figure 3.19: Flood impact map of the surrounding land along Mölndalsån. Source: MCF [20].



Figure 3.20: Flood impact map of the surrounding land along Mölndalsån, zoomed in on the more vulnerable areas. Source: MCF [20].

3.6.1 Temporary storage

A previous report by Sweco investigated the possibility of using Mölndalsån as temporary storage during periods of high sea level. The strategy considered was to manually lower the river level to +1.0 m before high sea levels are expected. This level represents the lowest permitted water level according to the water permit, due to the stability of the canal walls. Once this level is reached, the regulating structures must be closed to prevent the water level from falling below +1.0 m. After closure, the incoming river flow gradually refills the available storage volume. According to the report, the time required to lower the water level would vary between 2-6 hours depending on the inflow. The timing of the lowering was therefore considered important. If lowering is initiated too late, the water level may not have enough time to reach +1.0 m before the high sea level occurs. On the other hand, if it is initiated too early, incoming river flow may partly refill the available storage volume before the event begins.

The report further estimated that the storage capacity between water levels of +1.0 m and +2.0 m is approximately 120 000 m³ for the section from Mölndal to Slussen and the inlet to the culverts in Gullbergsån. The same report estimated that additional gates at the outlets of Stora Hamnkanalen and Rosenlundskanalen could increase the storage capacity to 195 000 m³.

3.7 Previous research on flow regulation

Similar hydraulic structures are used in other parts of the world to protect against both river and coastal flooding. Two examples are the IJssel Barrier in the Netherlands and the Thames Barrier in England. Although these structures are considerably larger than those in Mölndalsån, they operate according to similar principles and can be closed when elevated downstream water levels are forecast [21].

The IJssel Barrier is a vertical lift gate, which functions similarly to a sluice gate but on a much larger scale. When fully opened, the gate can be raised above the water surface. The structure is designed to protect against a 4 000 year return period on the river side and a 10 000 year return period on the sea side. It is manually operated and closed when a sea level of +2.25 m is forecast [21].

The Thames Barrier is located in London, where large tidal variations occur. The barrier is designed for a 1 000 year return period and is manually operated based on forecasts of both river discharge and tide levels [22]. The barrier is closed during low tide before the expected high water level occurs, allowing the river upstream to temporarily function as a storage basin. Once the tide has turned and the water levels on each side of the barrier have equalised, the barrier is opened again [21].

Since 2000, the frequency of closures of the Thames Barrier has increased. Approximately half of the closures have been caused by high river discharge and the other half by elevated sea levels and tides [22]. The increasing number of closures highlights the growing challenge of managing combined river and coastal flooding under changing climate conditions. This suggests that the operation of regulating structures is likely to become increasingly important in the future.

These examples illustrate that active operation of hydraulic structures is an established method for reducing flood risk in systems affected by both river discharge and high sea levels. This makes them relevant reference cases for Mölndalsån, where flood risk is influenced by both upstream discharge and downstream sea level.

4 Theoretical Background

This section presents the theoretical background relevant to the study, including hydrodynamics in open channel flow, coastal processes affecting sea level, compound flooding, flow regulation, risk and return periods.

4.1 Hydrodynamics – Shallow water equations

The hydrodynamics of the model is based on the shallow water equations, which describe unsteady flow in shallow water bodies such as rivers, channels, and coastal areas. To simplify complex three dimensional flow into a more practical form, several assumptions are made [23].

The main assumptions are:

- The water is incompressible and homogeneous, meaning that the density is constant.
- The bottom slope is small and can be approximated as horizontal.
- The flow direction is parallel to the bottom.
- Vertical accelerations are negligible.
- The pressure varies hydrostatically.

With these assumptions, the flow can be represented using a one dimensional form of the shallow water equations. This results in two governing equations, the continuity equation 4.1, and the momentum equation 4.2.

The continuity equation, also referred to as the mass balance, describes the conservation of water within a control volume. A change in inflow or outflow must therefore result in a change in storage, which is expressed as a change in water level. That is to say, if the discharge decreases due to a reduction in cross sectional area, water will accumulate upstream of the reduction, increasing the water level and finding a new balance [23].

The momentum equation describes the movement of water due to forces acting on the flow. These include inertia, pressure forces caused by the water surface slope, frictional resistance, and external forces. Namely, a steeper water surface slope increases the pressure gradient and therefore accelerates the flow [23].

Continuity equation

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0 \quad (4.1)$$

Momentum equation

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left(\frac{Q^2}{A} \right) = -gA \frac{\partial h}{\partial x} + gA (S_b - S_f) \quad (4.2)$$

where

- Q = discharge [m^3/s]
- A = cross-sectional area [m^2]
- t = time [s]
- x = distance along the channel [m]
- g = gravitational acceleration [m/s^2]
- h = water level [m]
- S_b = bed slope [-]
- S_f = friction slope [-]

Together, these equations describe the relationship between water level and discharge, and determine how fast the flow and storage respond to changes in inflow, boundary conditions, and channel geometry.

4.2 Coastal processes

When analysing flooding in coastal areas, it is important to consider the factors that contribute to increases in sea level. These increases can be either temporary, caused by storms and meteorological conditions, or long term caused by global sea level rise. The different factors contributing to elevated sea levels can occur simultaneously, and together they can significantly increase the total water level.

4.2.1 Extreme water levels

Temporary increases in sea level are often referred to as extreme water levels. These increases are primarily caused by meteorological factors such as wind, atmospheric pressure, and tides. Strong winds and low atmospheric pressure often occur together during storms, and the resulting rise in sea level is called a storm surge. Such events can last from a few hours to more than a day, depending on storm development [11].

Wind pushes water towards the coast through shear stresses acting on the water surface due to friction. This leads to an accumulation of water near the shoreline, resulting in a higher water level known as wind step up. On the west coast of Sweden, where Gothenburg is located, westerly winds are common and can push water from the Atlantic Ocean into Kattegatt. Additionally, the low atmospheric pressure associated with storms also contributes to an increase in sea level, normally about 1 cm per 1 hPa decrease in pressure. However, wind set up is usually the dominant contributor [11].

Tides are caused by astronomical forces, primarily the gravitational pull of the moon. They are regular and predictable, with an approximately 12 hour interval from peak to peak. The tidal range in Kattegatt is relatively small, approximately 25 cm. The magnitude of the tides is influenced by factors such as bathymetry, coastal topography and the shape of the shoreline as well as the lunar cycle [24].

4.2.2 Sea level rise

Long term sea level rise is a global challenge affecting many coastal regions and develops gradually over decades to centuries. Two main processes contribute to this increase, the melting of glaciers and the thermal expansion of water as its temperature rises, both of which are related to global warming [24].

Future sea level rise is often estimated using climate scenarios known as SSP, Shared Socioeconomic Pathways. These scenarios describe different possible future greenhouse gas emissions and their related climate impacts. One of the most extreme scenarios is SSP5-8.5, which represents a high emission pathway and therefore results in the largest predicted sea level rise [25].

For Gothenburg, projected sea level rise by 2100 varies depending on the scenario, with mean increases ranging from 26 to 64 cm, as shown in Figure 4.1.

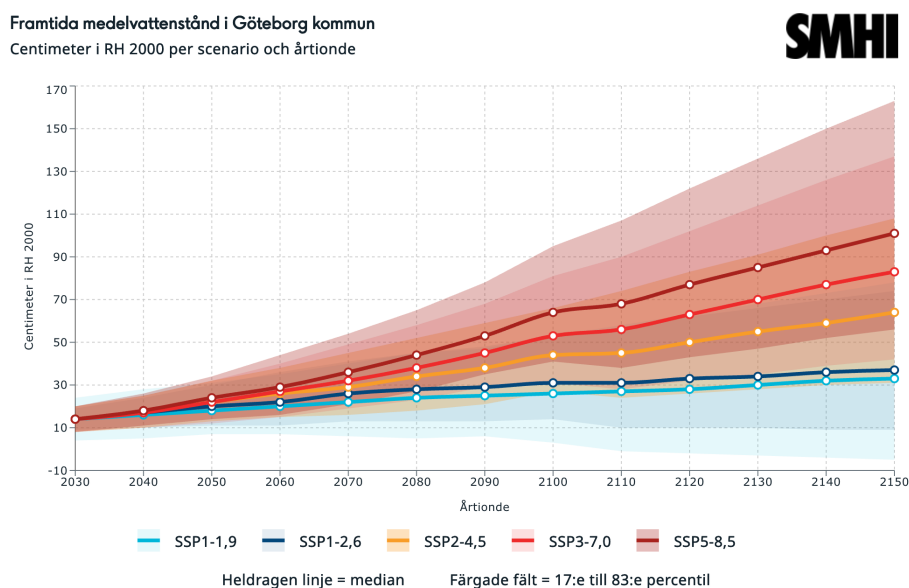


Figure 4.1: Future projected sea levels for Gothenburg. Source: SMHI [25].

4.3 Compound flooding

Traditionally, flood factors such as coastal water levels, river discharge and rainfall have been studied separately. However, in reality, these factors can occur simultaneously or within a short time interval, which may lead to more severe flooding. This situation is referred to as compound flooding [26].

Compound flooding can result from a single meteorological event, for instance tropical storms that generate both rainfall and elevated sea levels. It can also occur when independent events coincide, such as a spring flood due to snowmelt and a storm surge. The interaction between these factors makes compound flooding complex and more difficult to predict. Return periods are also difficult to estimate, since combinations of several events are generally less frequent than each event separately. In addition, the peak river discharge due to rainfall may occur with a time lag depending on the catchment, which further complicates the situation [26].

Research indicates that the likelihood of compound floods is increasing due to factors such as urban development, rising sea levels, and changing storm patterns. Treating flood factors as independent events may thus underestimate flood risk. Furthermore, mitigation measures designed to reduce one type of flooding may increase the risk of another, for instance coastal protection structures may restrict drainage and thereby worsen flooding caused by rainfall [26].

4.4 Flow regulation

Flow regulation in river systems serves several purposes. These include reducing flood risk, diverting flow, retaining water, and maintaining water levels. In addition, it supports functions such as irrigation, navigation, hydropower production, recreation and drinking water supply [16].

Different types of hydraulic structures can be used to regulate flow, including dams, gates, canals, weirs, culverts and basins. For movable structures, operation is important as decisions must be made regarding when and how to adjust the structures [16].

Operational strategies can be based on historical data, real time measurements, and forecasting of hydrological and meteorological conditions. Regardless of the approach, reliable data is essential, as inaccurate information may increase the risk of failure and lead to significant consequences [16].

Flow regulation may also involve a balance between upstream and downstream conditions, as measures that reduce flood risk in one area may increase it in another [16].

4.5 Risk and return periods

When discussing flood risk, two key components are considered, probability and consequences. Risk is commonly defined as the combination of these two factors. This means that an event with moderate probability and consequences may represent a higher risk than an event with severe consequences but a very low probability [24].

One common way to describe the probability of extreme events is through return periods. The return period is calculated from the annual exceedance probability and expresses the average recurrence interval for an event of a certain magnitude. For instance, a flood with a return period of 50 years corresponds to an annual probability of 2% and is therefore expected to occur on average once every 50 years. However, all events are statistically independent, meaning that they may still occur the year after each other. This is particularly important when interpreting short time series, where multiple extreme events may give a misleading impression of the long term probability. When estimating return periods it is therefore important to use long time series in order to avoid over or underestimation [24].

When planning flood protection measures, the chosen design return period indicates the level of risk one is willing to accept. Designing for a high return period reduces the likelihood of flooding, but it also means that most of the time it will not be fully utilised. On the other hand, designing for a lower return period implies one must accept that flooding may develop more frequently [24].

5 Data employed and analysis

Data were collected and analysed to describe the present hydraulic conditions in the study area and to define representative boundary conditions for the model. The analysis included historical sea level data, river flow data and information on the current water permit. This was done to define representative scenarios for evaluating the hydraulic response of Mölndalsån under different combinations of sea level and river inflow. The analysis resulted in three sea level scenarios and three river flow scenarios, which were later combined in the simulations.

5.1 Sea level data

Sea level data were obtained from measurement stations operated by SMHI along the Gothenburg coast and in Göta älv. Six stations were considered relevant for representing the sea level near the outlet of Mölndalsån, as shown in Figure 5.1. The location, name and available time series for each station are presented in Table 5.1 [27].

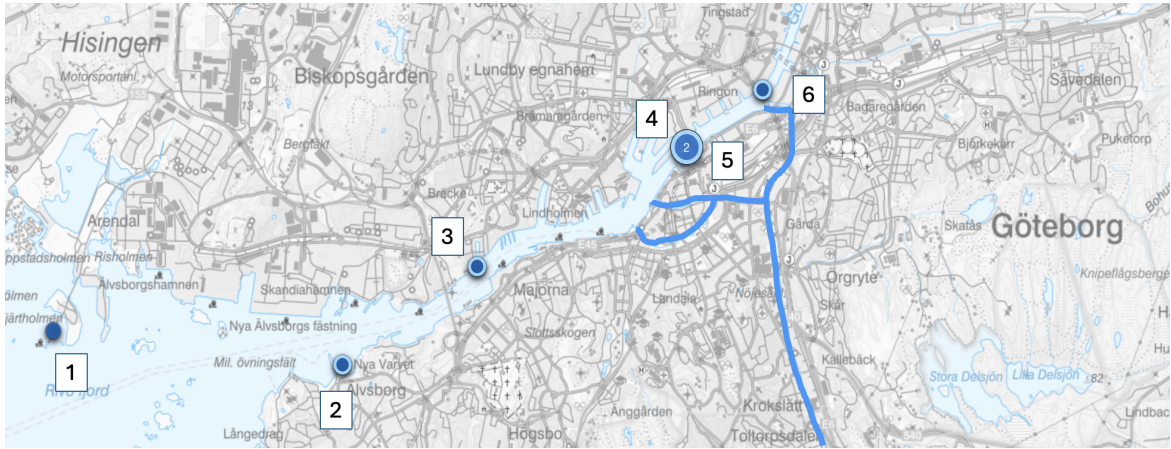


Figure 5.1: Sea level measurement stations around Gothenburg, marked 1-6, with names presented in Figure 5.1. Mölndalsån is marked as blue lines [27].

Table 5.1: Time series of sea level measurement stations in Gothenburg from SMHI [27].

Station	Time series	Number
Torshamnen	1967-2023	1
Tångudden sjöv	2019-ongoing	2
Eriksberg	2013-ongoing	3
Göta älv bro	2010-2013	4
Hisingsbron	2023-ongoing	5
Tingstadstunneln	2013-ongoing	6

The stations located closest to the study area have relatively short time series, whereas Torshammen provides a longer and more continuous record. As a result of this, Torshammen was selected as the primary station for further analysis.

The sea level series from Torshammen was further analysed in Excel in order to define representative downstream boundary conditions for the hydraulic model. Three scenarios were selected:

- Mean water level, representing normal conditions
- 99th percentile water level, representing elevated levels
- Extreme water level, representing an extreme event

Percentiles were selected instead of return periods in order to obtain representative sea level scenarios directly from the available time series without performing an extreme value analysis. An extreme value analysis would require additional statistical analysis, which is beyond the scope of this thesis. Percentiles was hence considered sufficient for defining comparable sea level scenarios for the hydraulic simulations.

The historical sea level data from Torshammen are presented in Figure 5.2. The dataset spans several decades and shows large variations between normal and extreme conditions. Based on calculations preformed in this study, the mean sea level is approximately 7 cm, while the 99th percentile is 67.5 cm and the maximum recorded value is 155.1 cm. This implies that storm events can generate considerably higher water levels.

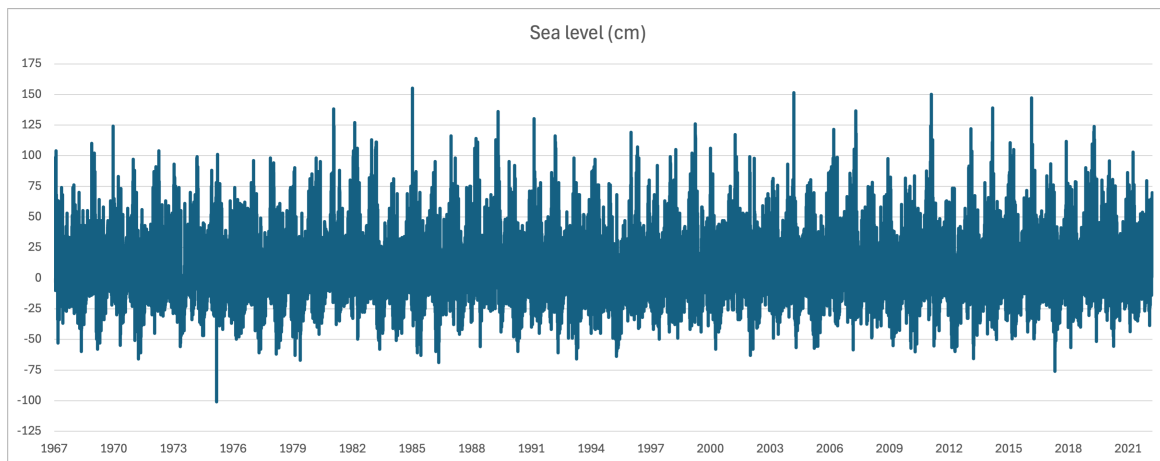


Figure 5.2: Historical sea level at Torshammen from 1967 to 2023, relative to RH2000.

To define the extreme sea level scenario, the time series was sorted from the highest to the lowest water level. The 20 highest observations were reviewed individually in order to assess whether they represented actual storm events or possible measurement errors, which are presented in Table 5.2. Several of the highest values were connected to the same storm events, with peaks around 150 cm. These events often consisted of multiple consecutive high values, indicating that extreme sea levels may persist for several hours rather than occurring only as isolated peaks.

Table 5.2: Twenty highest recorded sea levels at Torshamnen.

Date	Sea level [cm]
1985-11-06	155.1
1995-11-06	154.1
2005-01-08	151.3
1985-11-06	151.1
2011-12-10	150.2
1985-11-07	149.1
2016-12-26	147.3
1985-11-07	147.1
1995-11-06	145.1
2005-01-08	145.1
1985-11-06	142.1
1985-11-07	142.1
2011-12-10	141.1
2011-12-10	139.8
2015-01-11	139.0
2011-12-10	138.3
1981-11-24	138.1
2016-12-26	137.6
1985-11-06	137.1
2015-01-10	137.1

In addition to peak levels, the duration of high sea level events was analysed. Events during which the water level exceeded +1.0 m for at least two consecutive hours were identified. A minimum duration of two hours was applied in order to exclude short lived peaks, while the threshold level of +1.0 m was selected because this represents the lowest level to which the river can be lowered under the current regulation strategy. The duration analysis is relevant for evaluating alternative operating strategies for the hydraulic structures, since the effect of closing gates depends not only on the peak sea level but also on how long the elevated sea level persists.

The duration of the identified events are presented in Figure 5.3. The results show that high sea level events can last up to 25-26 hours, although shorter durations are more common. The cumulative relative frequency distribution in Figure 5.4 further confirms that most events are relatively short, while a small number have significantly longer durations.

The calculated duration does not represent the full duration of each storm event, but only the period during which the sea level remains above +1.0 m. Some exceedance periods may therefore belong to the same meteorological storm event and occur within a relatively short time after each other. Most of the selected storm events are seperated by months or years. Nevertheless, among the selected periods that occur close in time, the shortest gap between two consecutive periods is five hours, while the average gap is about nine hours.

Based on the sea level analysis, the selected sea level scenarios used in the hydraulic simulations are, the mean of 7 cm, the 99th percentile rounded up to 70 cm, and 150 cm for the average of the extreme scenarios.

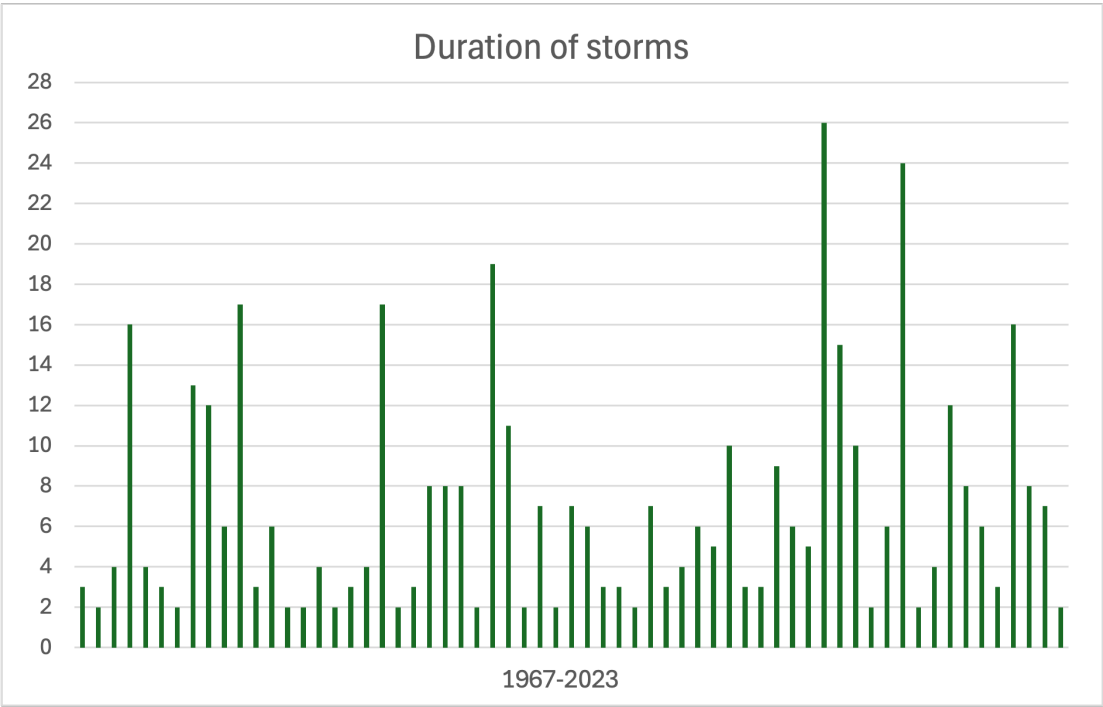


Figure 5.3: Durations of the identified extreme events.

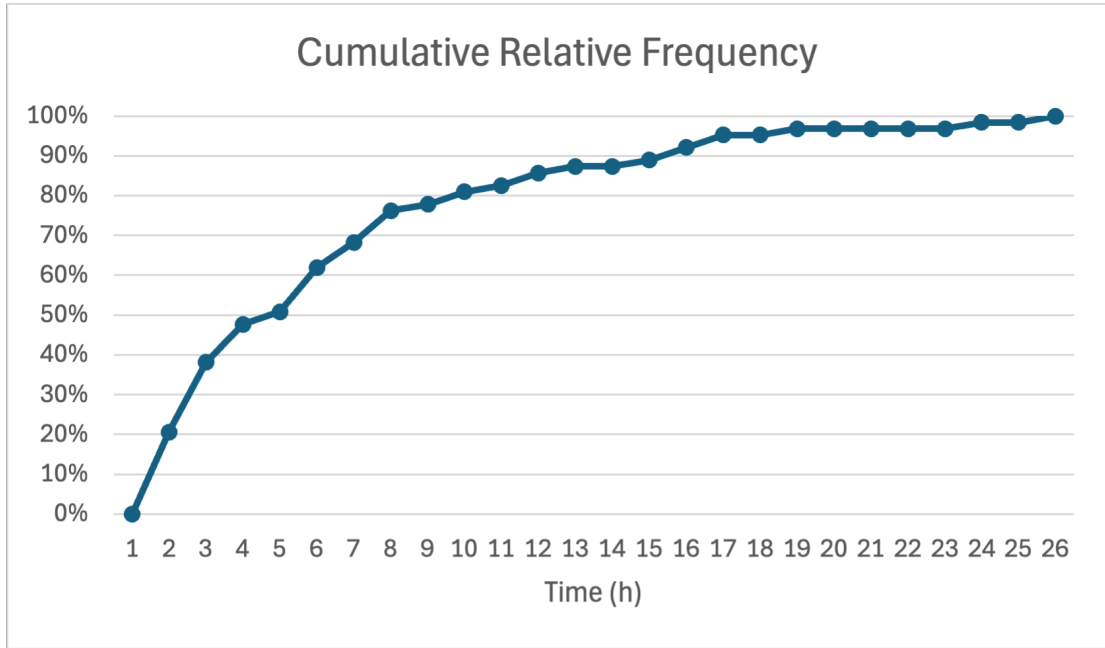


Figure 5.4: Cumulative relative frequency of the durations of the identified extreme events.

5.2 River flow

River flow data were obtained from Göteborgs Stads Stadsbyggnadsförvaltning, for the period 2011-2026. The dataset includes daily average water levels at four locations, Mölndal C, Skårs led, upstream of Gårda dämme and upstream of Slussen. It also includes daily average discharge from Stensjön, Slussen and Gårda dämme [28].

Water levels are measured directly, whereas discharge is calculated based on measured water levels and cross sectional areas [13]. The exact calculation procedure was not available for this study, and the discharge values were therefore treated as estimated rather than directly measured values. Negative discharge values were excluded from the analysis, as they were assumed to represent measurement or calculation errors.

The river flow data were analysed in Excel in order to define representative upstream inflow conditions for the model. Three scenarios were selected:

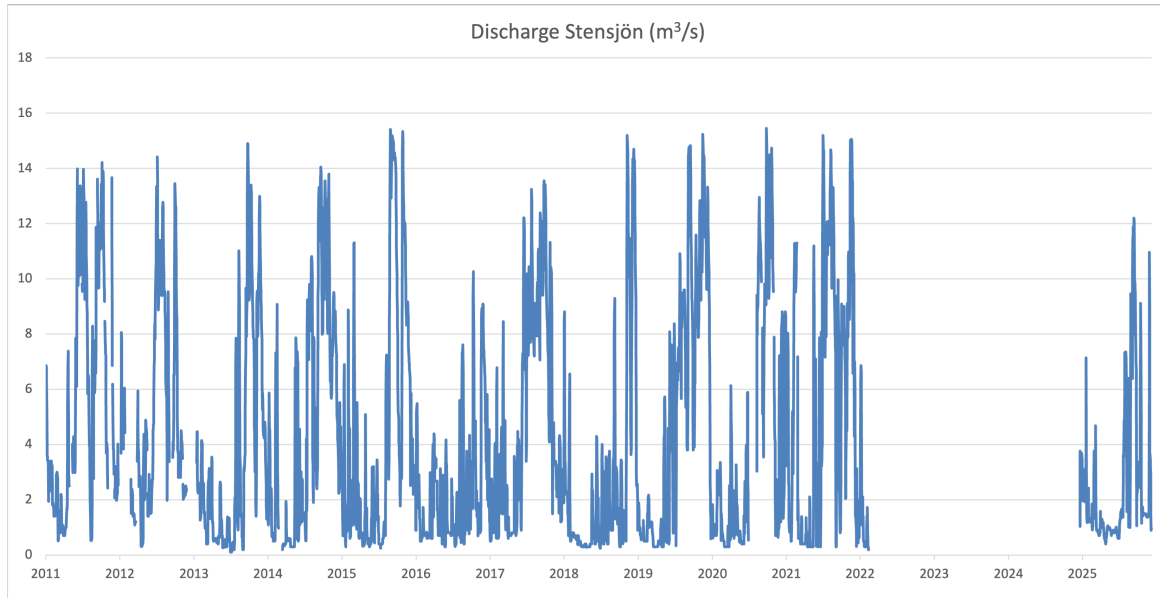
- Average discharge, representing normal conditions
- 99th percentile discharge, representing elevated flow conditions
- Maximum permitted discharge according to the current water permit, representing an extreme flow scenario

The water level upstream of Gårda dämme had a mean value of +1.4 m and a 99th percentile of +1.45 m. The river discharge statistics used for scenario selection are presented separately in Table 5.3.

Table 5.3: Discharge and water level statistics along Mölndalsån [28].

Variable	Mean [m^3/s]	99th percentile [m^3/s]
Discharge Stensjön	4.2	14.6
Discharge Gårda dämme	4.6	19.5
Discharge Slussen	0.8	10.2

The mean discharge at Stensjön is approximately $4.2 \text{ m}^3/\text{s}$, while the 99th percentile reaches $14.6 \text{ m}^3/\text{s}$. Figure 5.5 presents the discharge from Stensjön from 2011 until 2026. Downstream of Stensjön, Kålleredsbäcken also contributes to the flow in Mölndalsån. The mean flow in Kålleredsbäcken is $0.5 \text{ m}^3/\text{s}$, while the mean of the highest flows is $3.2 \text{ m}^3/\text{s}$. These values were therefore added to the representative mean and high flow scenarios from Stensjön, resulting in inflows of 5 and $18 \text{ m}^3/\text{s}$ respectively.

**Figure 5.5:** Graph of the discharge from Stensjön, from 2011 until 2026.

For the extreme flow scenario, the contribution from Kålleredsbäcken was not added to the maximum permitted discharge from Stensjön. According to the water permit, the maximum discharge from Stensjön should not be released if it would cause downstream flooding. Therefore, during high flow conditions in Kålleredsbäcken, the discharge from Stensjön is assumed to be reduced. The extreme scenario was therefore set to $27 \text{ m}^3/\text{s}$ which is the hydraulic capacity of Mölndalsån.

At the regulating structures, the discharge at Gårda dämme is generally higher than at Slussen, as shown in Figure 5.6. Under normal conditions, the mean discharge is 4.6 and $0.8 \text{ m}^3/\text{s}$ respectively. During high flow conditions, this difference becomes more noticeable, with Gårda dämme reaching $19.5 \text{ m}^3/\text{s}$ compared to $10.2 \text{ m}^3/\text{s}$ at Slussen. This indicates that most of the flow generally discharges through Gårda dämme.

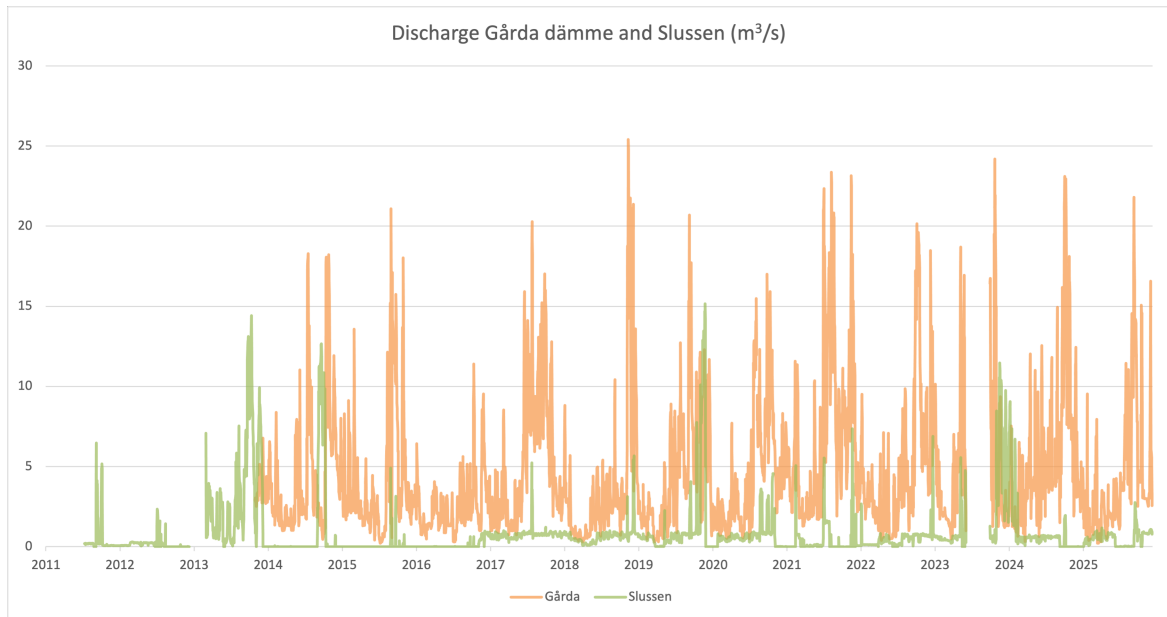


Figure 5.6: Graph of the discharge from Gårda and Slussen, from 2011 until 2026.

The water levels upstream of Gårda dämme remain relatively stable, as shown in Figure 5.7. The mean level is approximately 1.4 m and a 99th percentile is 1.45 m. This suggests that the regulating structure effectively maintains the upstream water levels close to its operational target of 1.45 m. The lowest recorded level at the same location is 1.16 m.

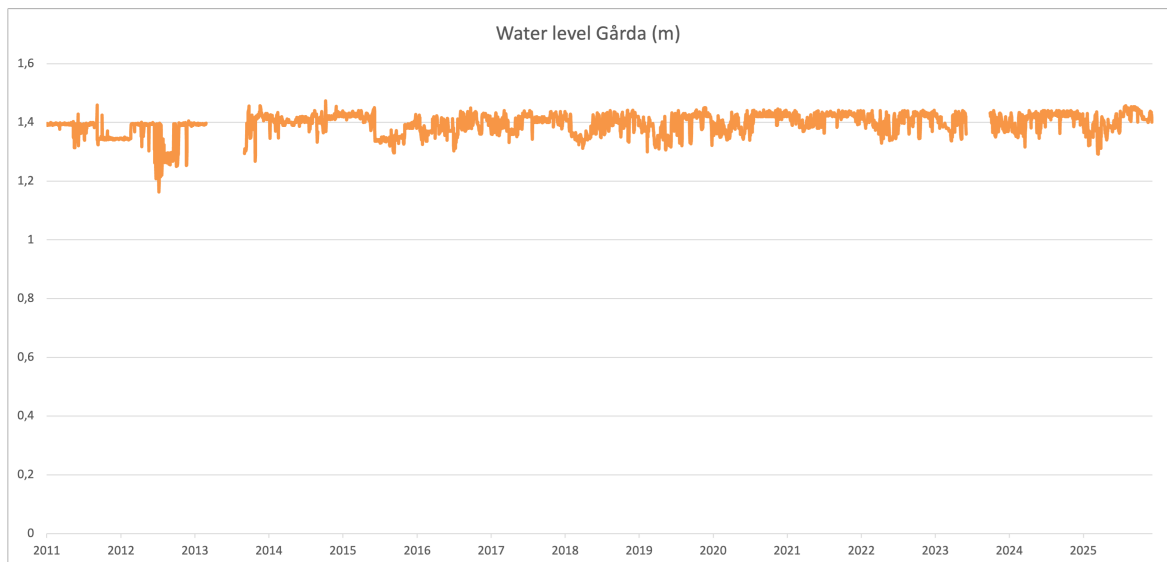


Figure 5.7: Graph of the recorded water levels upstream of Gårda from 2011 until 2026.

Some limitations in the dataset were identified, including several periods of missing data, which may affect how well extreme scenarios are represented. Furthermore, the operational target level may have been changed during the time period of the data.

5.3 Final scenarios

Based on the sea level and river flow analyses, representative scenarios were defined for use in the hydraulic simulations. The scenarios were selected to represent a range of hydraulic conditions rather than exact events, allowing the influence of river inflow and sea level to be compared. The final sea level scenarios consisted of mean sea level, 99th percentile sea level and an extreme sea level. The final river flow scenarios consisted of average flow, 99th percentile flow and the maximum permitted discharge according to the current water permit.

Combining the selected sea level and river flow scenarios resulted in nine steady state scenarios, presented in Table 5.4.

Table 5.4: Combinations of discharge and sea level used in the simulation scenarios.

Scenario	Discharge [m^3/s]	Sea level [m]
1	5.00 (<i>L</i>)	0.07 (<i>L</i>)
2	18.0 (<i>M</i>)	0.07 (<i>L</i>)
3	27.0 (<i>H</i>)	0.07 (<i>L</i>)
4	5.00 (<i>L</i>)	0.70 (<i>M</i>)
5	18.0 (<i>M</i>)	0.70 (<i>M</i>)
6	27.0 (<i>H</i>)	0.70 (<i>M</i>)
7	5.00 (<i>L</i>)	1.50 (<i>H</i>)
8	18.0 (<i>M</i>)	1.50 (<i>H</i>)
9	27.0 (<i>H</i>)	1.50 (<i>H</i>)

L = Low, M = Moderate, H = High.

An indication of the return periods of the more extreme scenarios can be obtained by comparing them individually with the values presented in Section 3.2 and 3.3. The extreme flow scenario in Mölndalsån of $27 \text{ m}^3/\text{s}$, is close to the reported 10 year flow of $26.8 \text{ m}^3/\text{s}$. The scenario can therefore be interpreted as approximately corresponding to a 10 year event. The medium flow scenario, $18 \text{ m}^3/\text{s}$, is lower than the reported 2 year flow of $20.5 \text{ m}^3/\text{s}$. However, these return periods refer to unregulated flow and should therefore only be used as approximate reference values.

For the sea level, two reference values are available for comparison. One represents conditions near Torshamnen, while the other represents conditions where Gullbergsån discharges into Säveån and Göta älv. The extreme sea level scenario used in the simulation is $+1.5 \text{ m}$. Compared with the Torshamnen reference value, this is between the 20 year sea level of $+1.43 \text{ m}$, and the 50 year sea level of $+1.53 \text{ m}$. However, compared with the Gullbergsån reference values, it is lower than the 10 year sea level of 1.63 m . The return period can therefore not be determined from a direct comparison alone. As discussed in Section 3.3, water levels during storm conditions may be higher further upstream in Göta älv than at the coast, which makes the estimated return period dependent on the reference location used.

These return periods refer to the individual flow and sea level events, not the combined compound flooding scenarios. A combination of both events would generally be less frequent than each event considered separately, and would therefore correspond to a longer return period. Nevertheless, under future climate scenarios, rising sea levels and increased precipitation may make high sea levels and high flow events more frequent, thereby shortening their return periods.

6 Model setup and implementation

This section describes the hydraulic model used in the study and the main assumptions made in the model setup. The existing MIKE+ model is first presented, followed by a description of the regulating structures at Gårda dämme and Slussen and the selection of critical locations for analysis. The calibration and validation procedure is then described. Finally, the simulation approach is presented, including the water level simulations and the temporary storage capacity analysis.

6.1 The MIKE+ rivers model

The hydraulic model was developed in MIKE+ Rivers by DHI. In this study, a one dimensional model was used, since the main purpose was to analyse water levels and flow distribution along the river system.

An existing MIKE+ model provided by DHI was used as the basis for the study. The model already contained the river network, cross section and hydraulic structures. The work in this study therefore mainly consisted of reviewing the existing model, modifying the regulating structures at Gårda dämme and Slussen, and defining appropriate boundary conditions and simulation scenarios.

The model includes the river system from the outlet of Stensjön to its outlets in Göta älv and consists of the branches Mölndalsån, Gullbergsån, Fattighusån, Rosenlundskanalen and a part of Sävån. The river bathymetry, cross sections and most hydraulic structures were mostly left unchanged from the original model, although minor adjustments were made where necessary.

Hydraulic structures such as bridges were represented using culverts for the opening below the bridge deck, while weirs were used to represent overflow during high water levels. In total, the model contains 49 culverts, 24 weirs and two regulating structures.

The main changes made to the model during this study were:

- Definition of new upstream and downstream boundary conditions
- Update of the dimensions of the regulating structures at Gårda dämme and Slussen
- Relocation of the sensor to the correct position upstream of Gårda dämme
- Update of the gate operation rules to represent the current regulation strategy

The main model settings are presented in Table 6.1.

Table 6.1: Model setup used in MIKE+.

Parameter	Description
Model type	River network, Hydrodynamics
Coordinate system	Sweref99_12_00
Height reference	RH2000
Background map	OpenStreetMap
Rivers	Fattighusån, Säveån, Mölndalsån, Gullbergsån and Rosenlundskanalen
Cross sections	Approximately 230
Culverts	49
Weirs	24
Gates	2, Gårda dämme and Slussen
Boundary conditions	Inflow Mölndalsån, inflow Säveån, sea level at the last chainage of Rosenlundskanalen, Säveån and Fattighusån
Sensor	1, upstream of Gårda dämme
Simulation setup	Duration 3 days, adaptive time step 0.5–5 s

The modelled area and cross section locations are presented in plan view in Figure 6.5. A longitudinal profile of the river system is shown in Figure 6.1–6.4, where vertical lines represent cross section locations, the green line shows the right hand river bank and the purple line shows the left hand river bank. Since the model uses RH2000 as a height reference system, this thesis presents water levels and elevations relative to RH2000 unless otherwise stated.

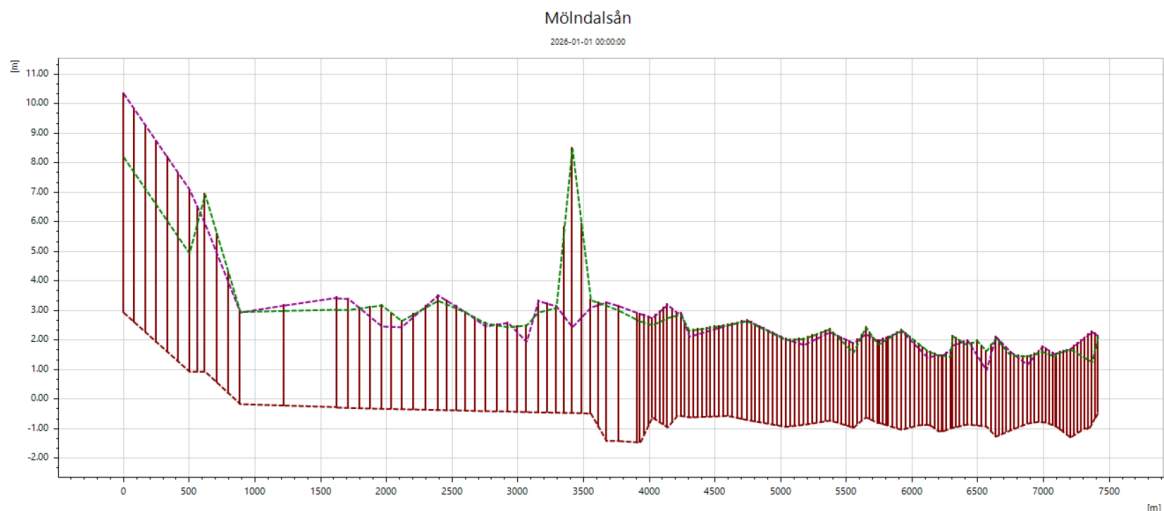


Figure 6.1: Longitudinal profile of Mölndalsån in the MIKE+ model. The green line shows the right hand river bank and the purple line shows the left.

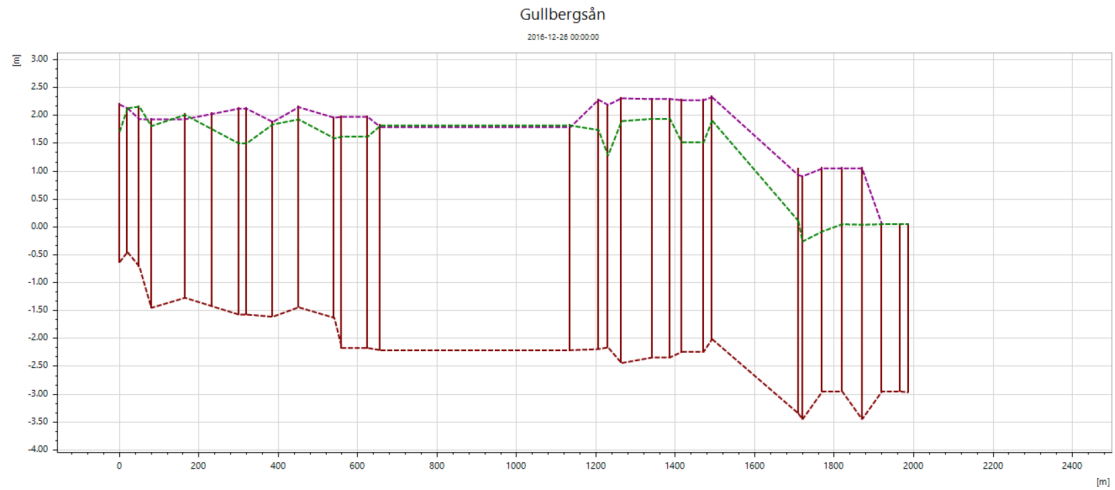


Figure 6.2: Longitudinal profile of Gullbergsån in the MIKE+ model. The green line shows the right hand river bank and the purple line shows the left.

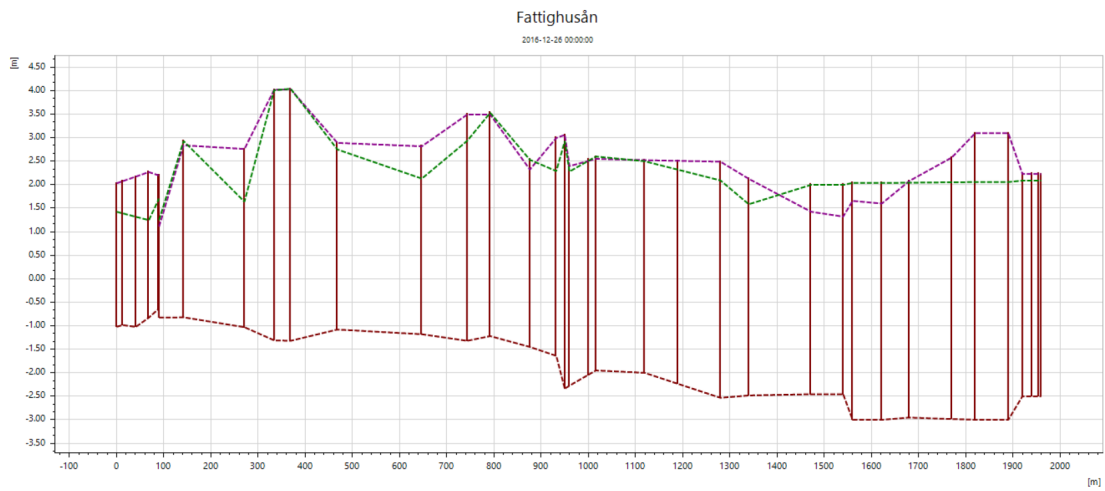


Figure 6.3: Longitudinal profile of Fattighusån and Stora Hamnkanalen in the MIKE+ model. The green line shows the right hand river bank and the purple line shows the left.

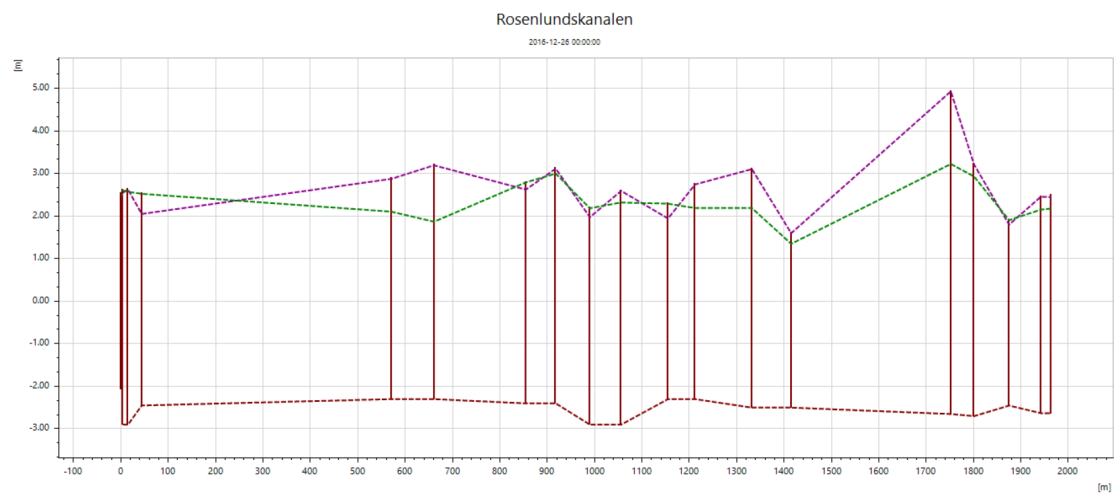


Figure 6.4: Longitudinal profile of Rosenlundskanalen in the MIKE+ model. The green line shows the right hand river bank and the purple line shows the left.

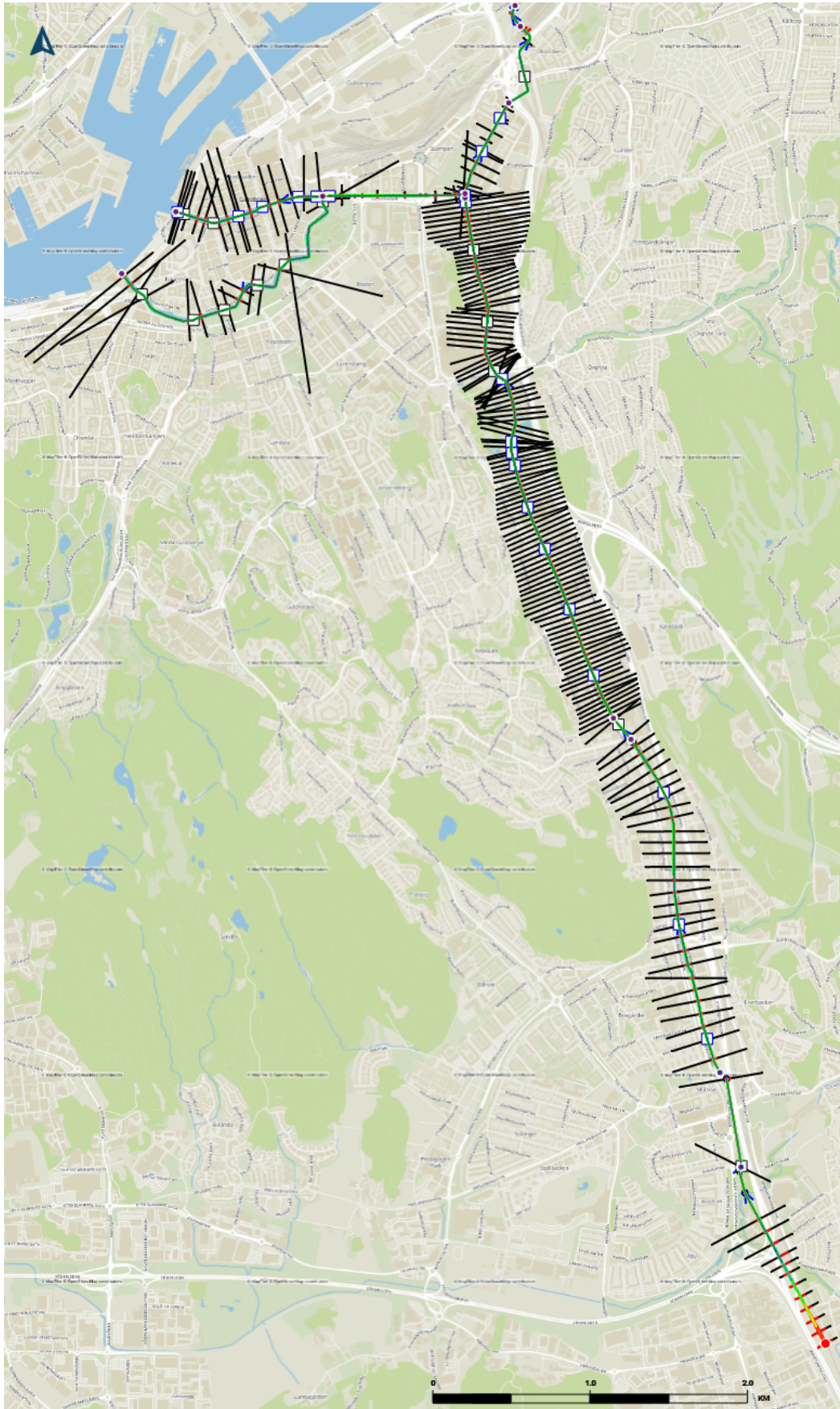


Figure 6.5: The modelled area in MIKE+, with cross section locations as black lines.

6.2 Regulating structures

The regulating structures at Gårda dämme and Slussen were represented in the model with a level of detail considered appropriate for the analysis of water levels and flood risk. Some operational assumptions were made in order to reduce model complexity and simulation time.

Gårda dämme was modelled as five underflow gates controlled using a PID controller. The controller was set to maintain a water level of +1.45 m upstream of Gårda dämme, corresponding to the current operating strategy. In reality, the five gates can be operated individually, however in the model all gates move simultaneously and therefore always have the same gate opening. As for the fish ladder, it was modelled as a culvert and the weir was not included.

Slussen was modelled as two underflow gates and two culverts. The underflow gates represent the regulated opening at the bottom of the structure, while the culverts were used to represent the overflow function. Unlike the real overflow structure, the culverts remain at a fixed level and are not actively regulated.

The operation of Slussen is controlled by the measured water level upstream of Gårda dämme. The gate opening follows the operating rules shown in Table 6.2. The bottom openings remain closed until the upstream water level reaches approximately +1.45 m, after which they are gradually opened in order to maintain this level.

Table 6.2: Gate control levels used for the operation of Slussen in the MIKE+ model.

Water level [m]	Gate bottom level [m]
-10	-2.07
1.44	-2.07
1.45	-1.95
1.50	-1.50
1.55	-1.00
1.60	-0.20
1.70	2.00
10	2.00

The gate operation was implemented in MIKE+ using a level controlled table. In reality, both the physical structure and the operation of Slussen include additional details that are not fully represented in the model. However, the chosen representation was considered sufficient to reproduce the overall effect of the structure on water levels.

6.3 Selection of critical locations

The model consists of a large number of cross-sections and structures placed along a longitudinal profile. By taking to account the characteristics of the river and relate to

the MCF flood risk mapping in Section 3.6, locations along Mölndalsån relevant for detailed analysis were determined.

The longitudinal profile was used to identify low lying sections along the river where flooding is likely to develop first. The flood risk map was then used to determine whether these locations coincide with critical infrastructure, residential areas or other vulnerable land uses located close to the river.

The selected locations are therefore a combination of low lying areas and areas containing important infrastructure. Water levels and possible flooding at these locations were analysed in detail for each simulation scenario.

6.4 Model calibration and validation

A simplified steady state calibration of the hydraulic model was carried out by adjusting the bed roughness. The bed roughness was represented using Manning's n , which describes the resistance to flow along the riverbed and channel. A higher Manning's n corresponds to greater resistance, while a lower value represents a smoother channel with less resistance.

Three Manning's n values were tested in the calibration:

1. $n=0.04$
2. $n=0.037$
3. $n=0.033$

A homogeneous approach was applied, meaning that the same Manning's n value was used along the entire modelled river. In reality, roughness may vary along the river as a result of differences in river characteristics, hydraulic structures, vegetation and bed material.

The calibration was performed using selected historical events with different hydraulic conditions, including variations in river discharge and sea level. For each event, constant boundary conditions were applied based on observed data for measured flow in Mölndal and downstream sea level. The simulated levels were then compared with measured water levels at four locations along the river system:

- Mölndal C
- Skårs Led
- Upstream of Gårda dämme
- Upstream of Slussen

The comparison was used to evaluate how changes in Manning's n affected the simulated levels and how well the model reproduced the observed conditions. Based on the calibration, one Mannings n value was selected and validated against two additional historical events to assess its performance under independent conditions. The selected value was then used in the following simulations.

6.5 Water level simulations

Based on the data analysis, three sea level scenarios and three river flow scenarios were selected. When combined, these resulted in nine different simulation scenarios. The selected inflow and sea level for each scenario were applied as boundary conditions in the model.

Since this part of the study aims to assess the current flood situation, steady state simulations with constant inflow and sea level were used. This made it possible to determine the water level at the selected critical locations for each scenario. This approach was chosen to distinguish between the effects of river inflow and sea level, while also allowing direct comparison between the scenarios.

For each simulation, the maximum water level at the selected locations was extracted from the model results. These water levels were then compared with the cross sectional bathymetry of each location and the river bank elevations in order to determine whether flooding appeared. Where flooding occurred, it was also determined on which side of the river flooding first occurred to evaluate whether critical infrastructure was affected.

The results from the different locations were then compared for each scenario in order to determine whether the water level was primarily controlled by upstream river flow, downstream sea level, or both. This was done by comparing scenario groups where one boundary condition varied while the other was kept constant. Scenarios 1-3, 4-6 and 7-9 were used to assess the effect of increasing inflow under constant sea level conditions. Comparisons between scenarios 1, 4, and 7; 2, 5, and 8; as well as 3, 6, and 9 were used to assess the effect of increasing sea level under constant inflow conditions.

If the controlling factor differed along the river, the river system could be divided into sections based on their different hydraulic behaviour. This analysis can later be used to determine where different mitigation measures would be most effective.

6.6 Temporary storage capacity

The regulation strategy makes it possible to temporarily store water within the river system during periods of high sea level by keeping the regulating structures closed. The river can therefore act as a temporary reservoir. An additional analysis was performed to determine how long the structures can remain closed before the water level reaches the critical level upstream of Gårda dämme. The results were used to discuss whether the maximum closure time would be sufficient during high sea level events.

The simulations were carried out by setting the initial river level in the system to +1.0 m and closing the gates at both Gårda dämme and Slussen. Different constant inflows were then applied at the upstream boundary, where the lowest represented the minimum discharge from Stensjön and the highest represented the average flow from the data analysis. For each simulation, the time until the water level upstream of Gårda dämme reached +1.4 m was extracted. The extracted time therefore represents the maximum period during which the gates can remain closed for a given inflow. The threshold of +1.4m was used as an approximate normal operating level upstream of Gårda dämme.

Assuming a constant inflow, the stored water volume was estimated using Equation 6.1.

$$V = Q \cdot t \quad (6.1)$$

where V is the stored water volume [m^3], Q is the river inflow [m^3/s], and t is time [s]. The calculation was repeated for several inflows to determine the relationship between inflow and available storage in the river system.

Additional regulating structures at the discharge outlets to Göta älv have been proposed, referred to as inner barriers. Therefore, an alternative storage case was also investigated. In the first storage case, temporary storage was limited to the part of the river system upstream of Slussen and Gårda dämme, while water could still leave the system through the inner barriers. In the alternative case, the inner barriers were closed so that no water could leave the modelled river system. This allowed the entire river system, from the inner barriers and upstream, to contribute to the temporary storage. The simulation started from an initial river level of +1 m and continued until the water level upstream of Gårda dämme reached +1.4 m. As in the first case, the time required to reach this level was extracted for each inflow and used to estimate the stored volume.

7 Results and discussion

This chapter presents and discusses the results from the hydraulic simulations. The results are divided into four main parts, the identification of critical locations, calibration and validation of the model, simulated flooding under different combinations of sea level and inflow, and the estimated temporary storage capacity of the river system.

7.1 Critical locations

Eight critical locations were selected along the modelled river system, based on a combination of low bank elevations and surrounding land use. Their cross sections used to assess local flood thresholds are shown in Figure 7.1–7.8, while their locations are shown in Figure 7.9.

The locations are labelled A to H, starting from the most upstream point. They were selected to represent different types of potentially vulnerable areas along the river system, including critical infrastructure, residential areas, cultural heritage sites and low lying areas. The specific characteristics of each location are summarised in Table 7.1. Since flooding is defined as overtopping of river banks in this thesis, critical levels refer to local bank levels rather than specific elevations for nearby infrastructure and buildings.

Table 7.1: Selected critical locations and main reason for selection.

Location	Main reason for selection	Critical side
A	Close to hospital	Left
B	Railway and residential area	Right
C	Industrial area	Right
D	Low elevation	Both
E	Residential area and cultural heritage	Right
F	Fire station	Right
G	School and residential area	Both
H	Low elevation	Left

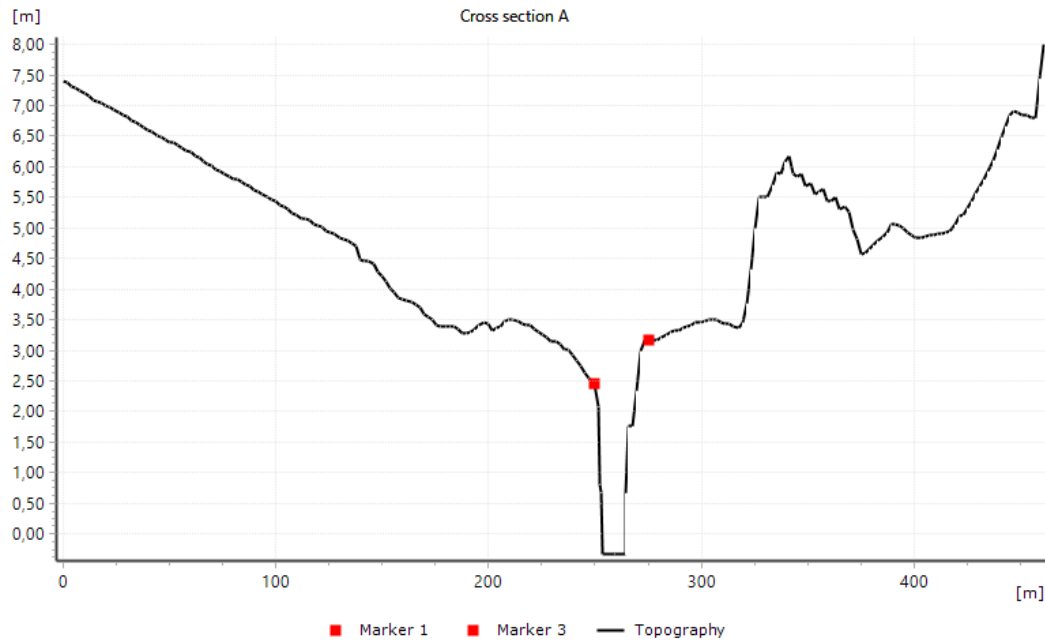


Figure 7.1: Cross section of the topography in location A, the red dots mark the bank levels on each side.

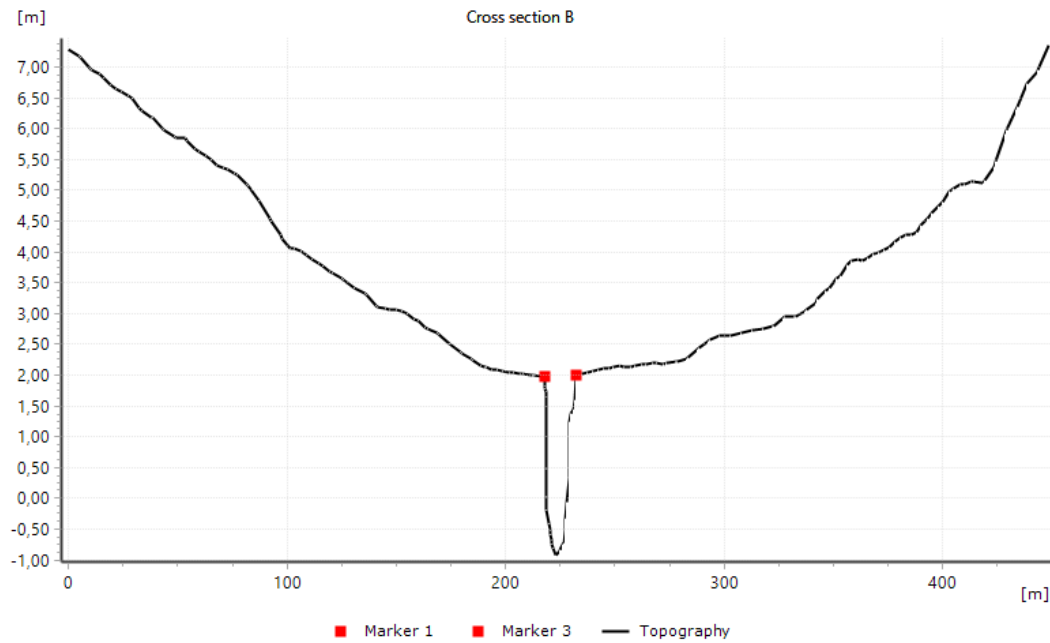


Figure 7.2: Cross section of the topography in location B, the red dots mark the bank levels on each side.

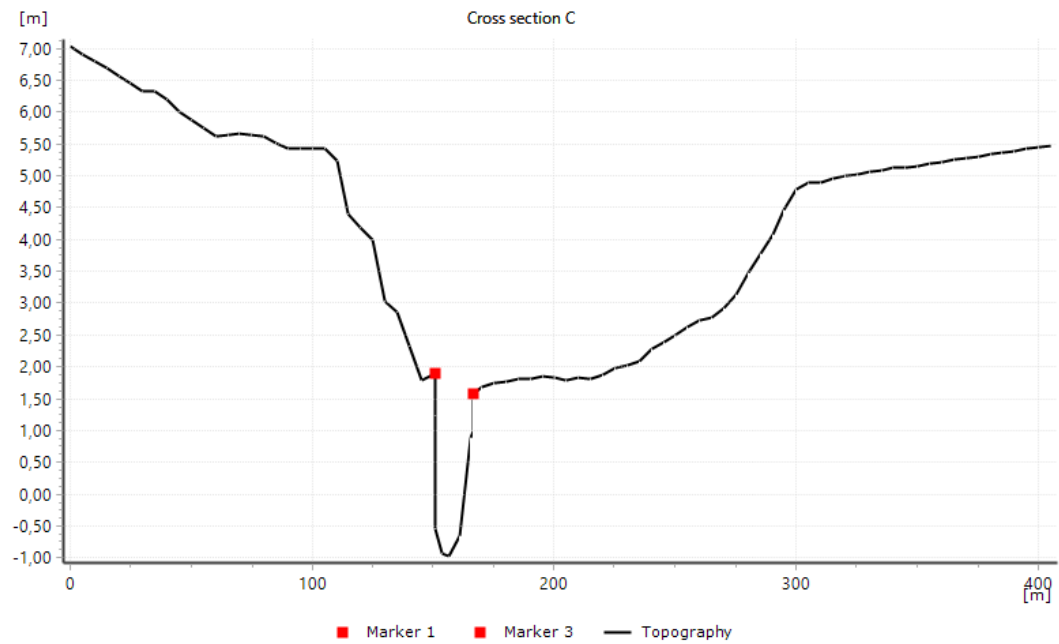


Figure 7.3: Cross section of the topography in location C, the red dots mark the bank levels on each side.

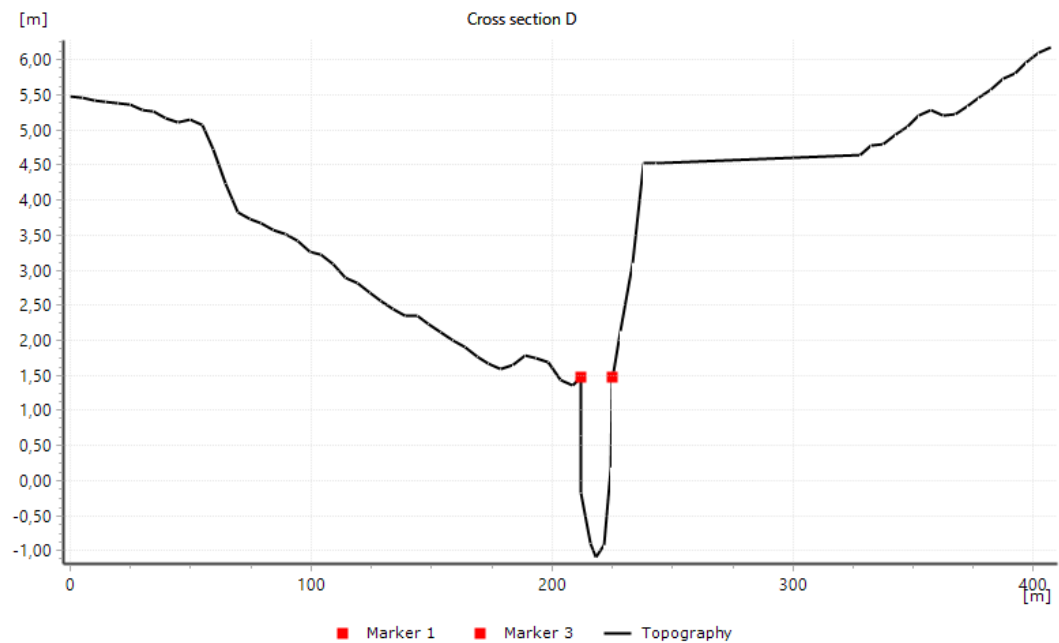


Figure 7.4: Cross section of the topography in location D, the red dots mark the bank levels on each side.

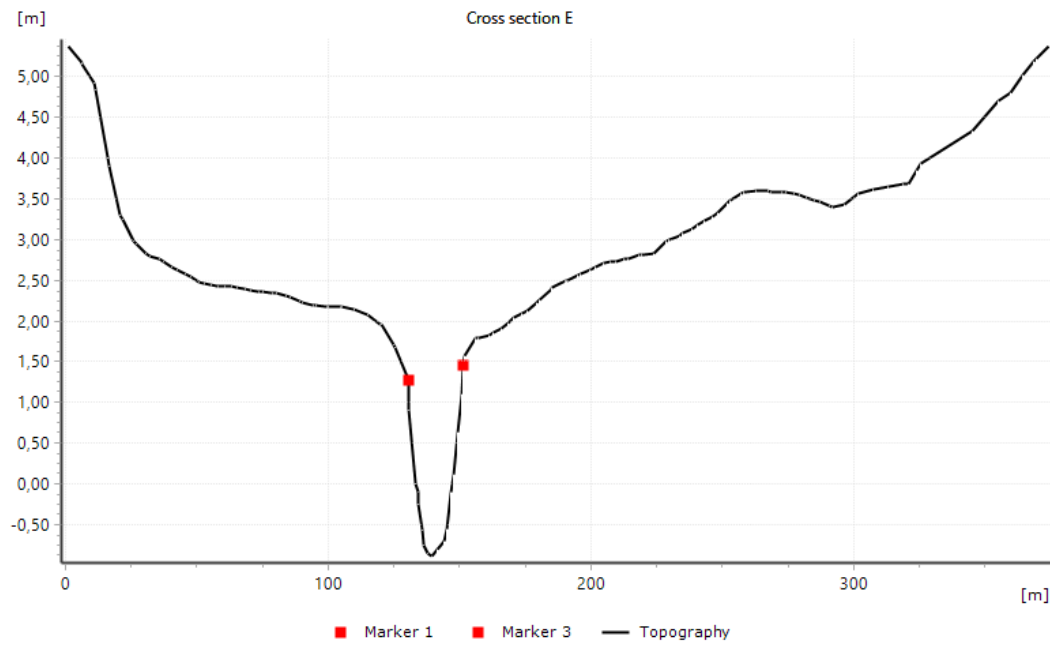


Figure 7.5: Cross section of the topography in location E, the red dots mark the bank levels on each side.

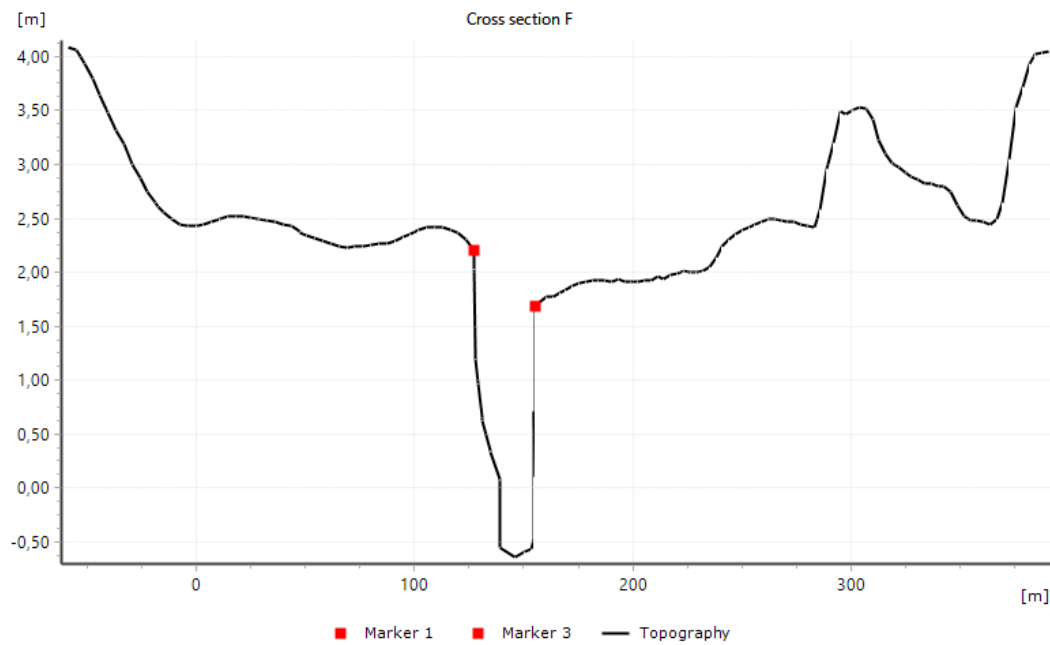


Figure 7.6: Cross section of the topography in location F, the red dots mark the bank levels on each side.

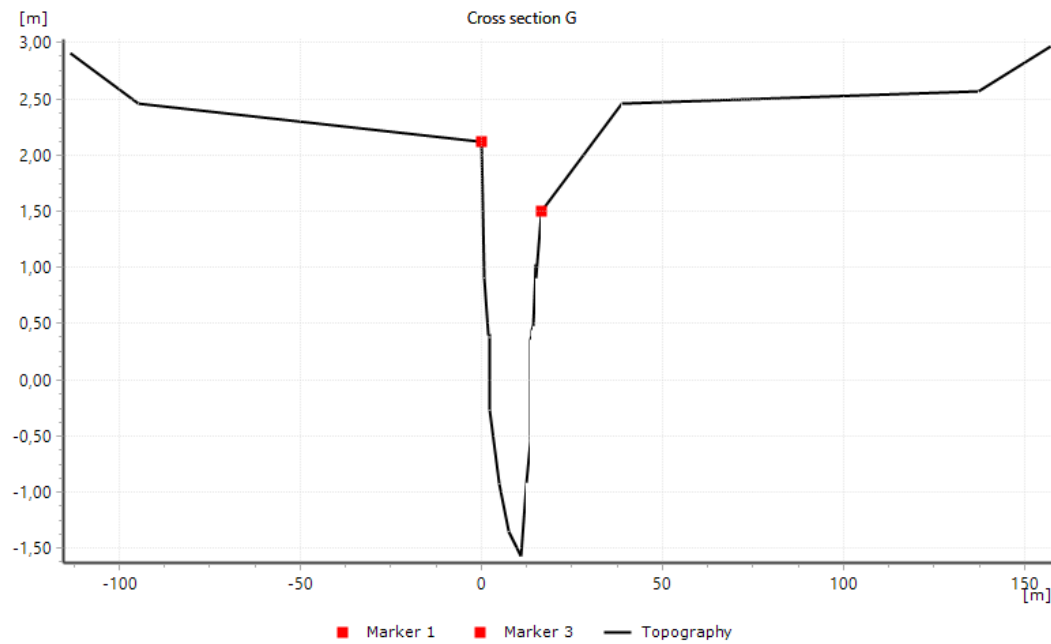


Figure 7.7: Cross section of the topography in location G, the red dots mark the bank levels on each side.

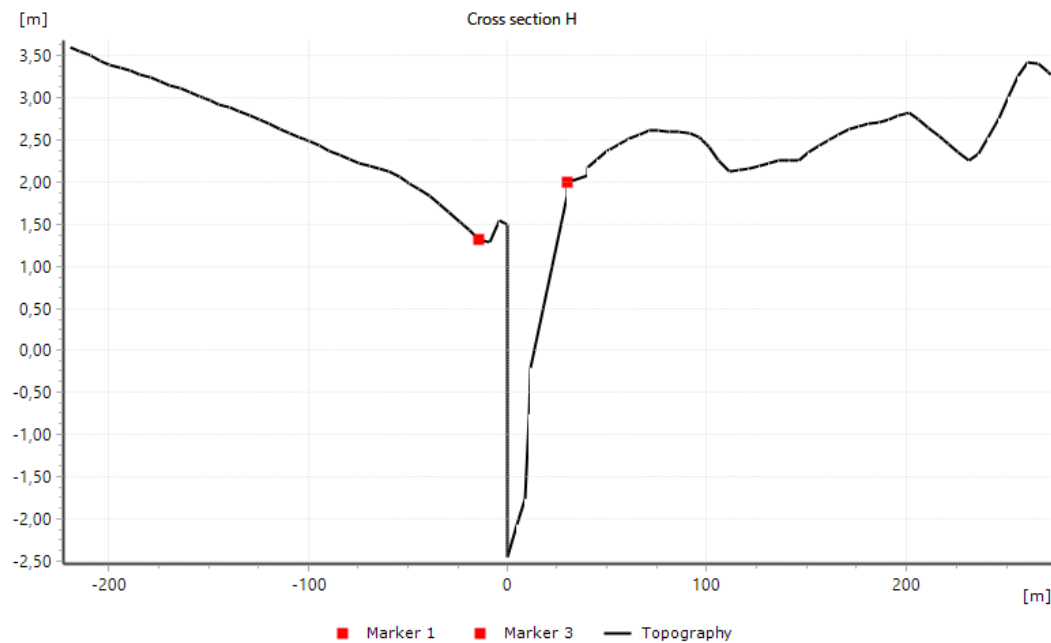


Figure 7.8: Cross section of the topography in location H, the red dots mark the bank levels on each side.

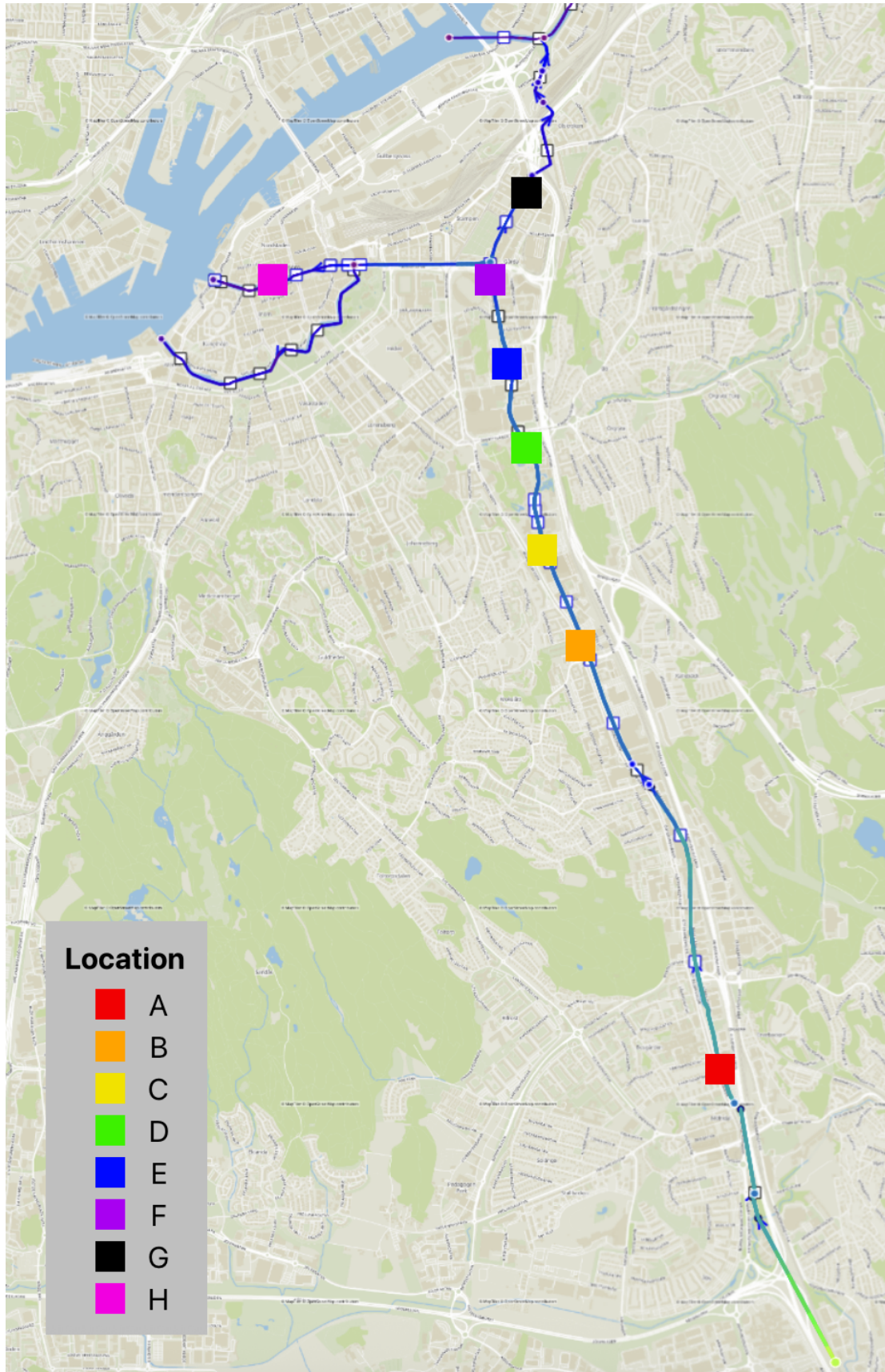


Figure 7.9: Locations of the selected critical locations along the modelled river system.

7.2 Calibration and validation

The calibration results are presented in Figures 7.10–7.12. Each figure represents a different historical event and compares measured and simulated water levels at four locations for the tested Mannings' n values.

The results show that the simulated levels have varying sensitivity to Manning's n along the river. The largest differences between the tested roughness values were observed at Mölndal C and Skårs led, while the levels upstream of Gårda dämme and Slussen were less affected. This implies that the downstream regulating structures had a stronger influence on the water levels in the downstream part of the river system than the bed roughness alone.

The observed water levels upstream of Gårda dämme and Slussen were generally lower than the simulated values. The simulated levels were close to the control level of +1.45 m, while the measured levels were often below this. This suggests that the regulation strategy during the observed events may have differed from the one applied in the model, for example as a result of different operational settings at the time. As this affects the water levels throughout the system, the calibration was mainly evaluated based on how well the simulations reproduced the relative water level profile. The control level used in the simulations was not adjusted, since the aim is to represent current operating conditions, for which +1.45 m is the relevant control level.

No single Mannings' n value provided the best fit for all the events and locations. During lower flow conditions, the lowest roughness value gave the closest fit between simulated and observed water levels, although the difference between tested Manning's n were mainly visible at Mölndal C. During higher flow conditions both $n=0.033$ and $n=0.037$ were close to the measured level at Mölndal C, while $n=0.037$ gave a more representative water level gradient along the river. Based on this, $n=0.037$ was selected for the final simulations.

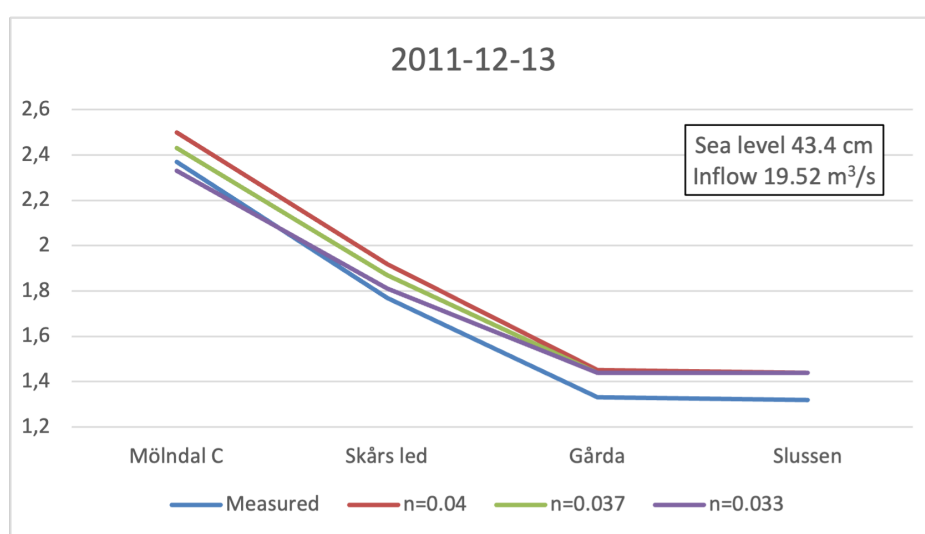


Figure 7.10: Calibration of Manning's n for the historical event on 2011-12-13, using measured water levels at four locations as reference points.

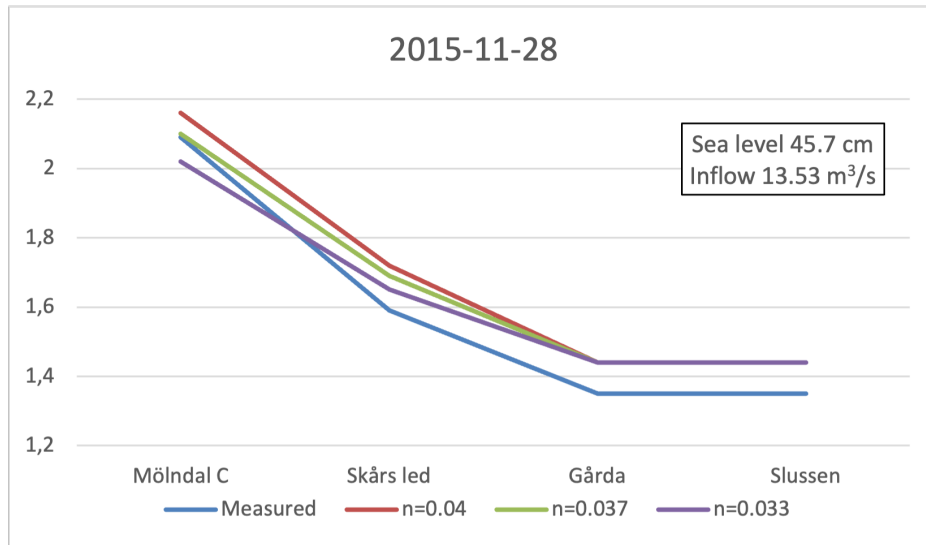


Figure 7.11: Calibration of Manning's n for the historical event on 2015-11-28, using measured water levels at four locations as reference points.

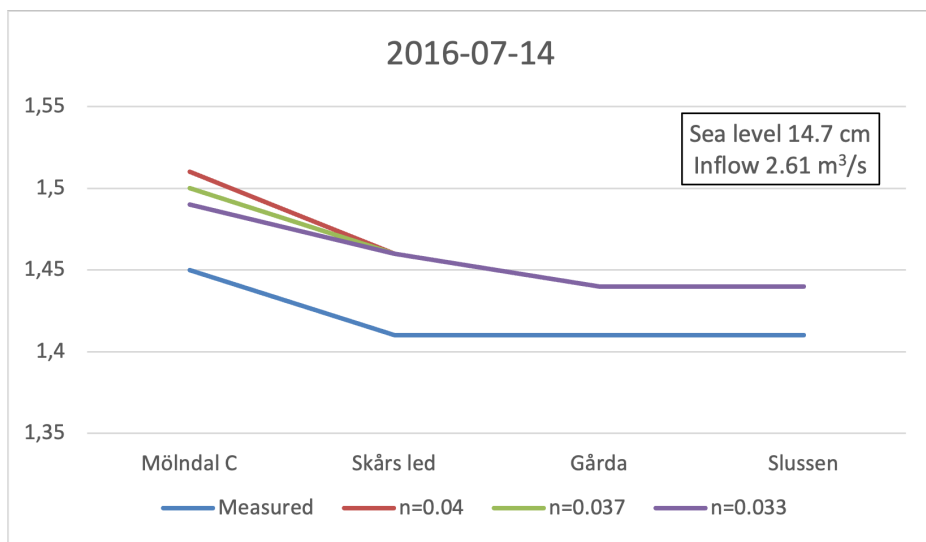


Figure 7.12: Calibration of Manning's n for the historical event on 2016-07-14, using measured water levels at four locations as reference points.

The selected Mannings n value was then evaluated against two additional historical events, as shown in Figure 7.13 and 7.14. The validation showed that the model reproduced the general water level pattern along the river system, although some differences between measured and simulated values remained. The largest difference was 10 cm at Gårda and Slussen, where the simulated values were higher than the observed. These deviations are likely related to differences in operational strategies and should be considered when interpreting the scenario results, particularly at locations where the simulated water level exceeds the bank level by less than 10 cm.

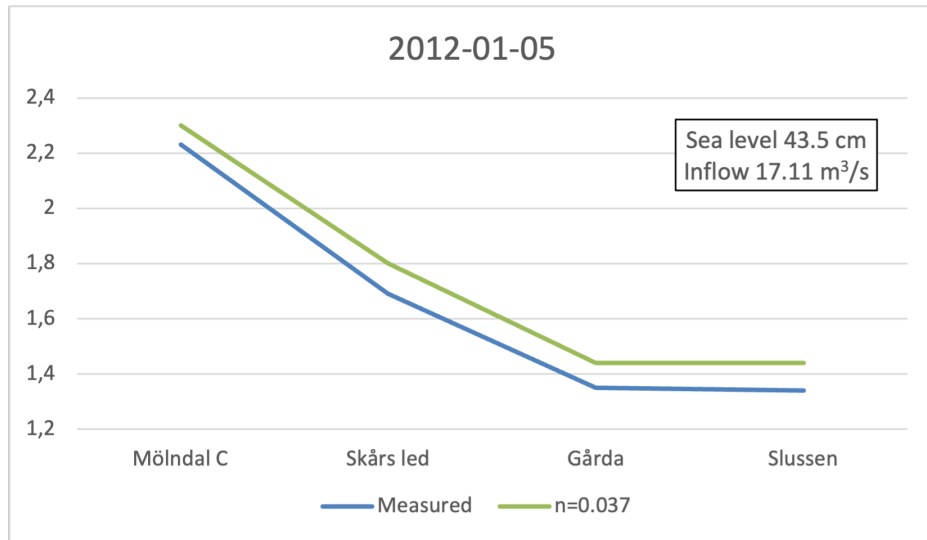


Figure 7.13: Validation of Manning's n for the historical event on data 2012-01-05, using measured water levels at four locations as reference points.

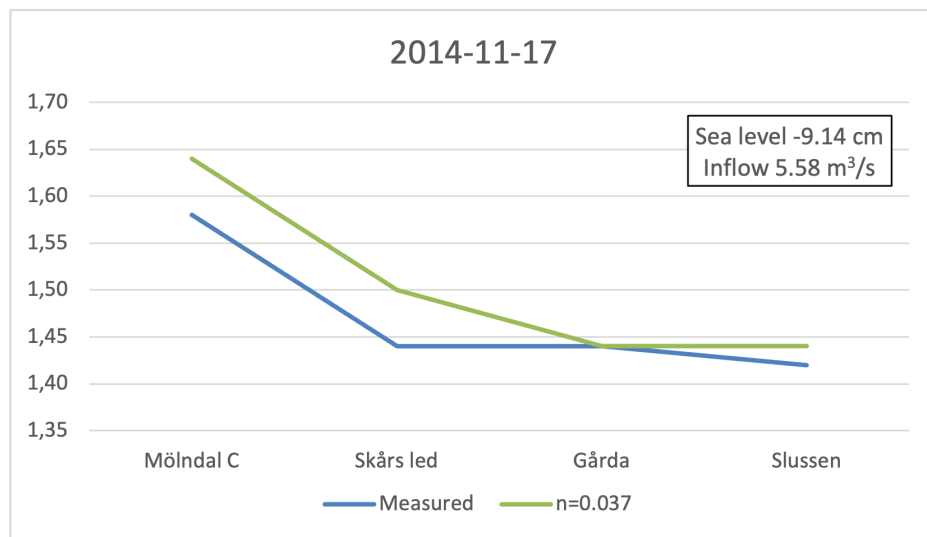


Figure 7.14: Validation of Manning's n for the historical event on data 2014-11-17, using measured water levels at four locations as reference points.

7.3 Water level simulations

The nine scenarios selected from the data analysis were simulated, and maximum water levels were extracted at the eight selected locations. These water levels were then compared with the corresponding bank levels to determine whether flooding took place. The results for each location are presented in Figure 7.15. By comparing the scenarios with constant sea level and increasing inflow, and scenarios with constant inflow and increasing sea level, it was possible to identify whether flooding at each location was mainly caused by river inflow, sea level, or a combination of both.

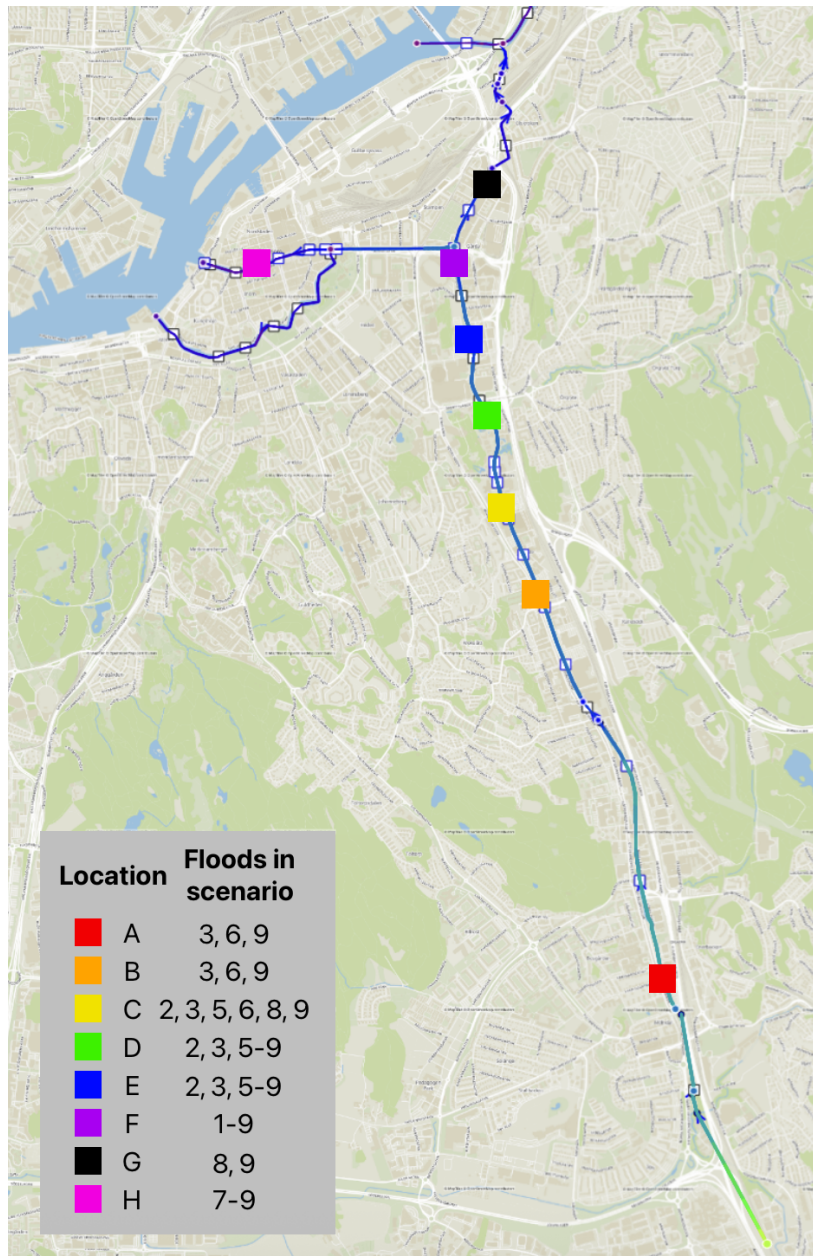


Figure 7.15: Map of the critical locations and presentation of which scenarios they get flooded.

Table 7.2 provides further detail by showing the difference between the simulated water level and the critical bank level at each location, expressed in centimeters. Where both banks were considered critical, the lower one was used for the comparison. Positive values indicate that the critical level was exceeded and are marked in red, while negative values indicate that no flooding occurred. Values marked in orange represent locations where the difference between the simulated water was within ± 2 cm of the bank level, or where flooding occurred but was smaller than 10 cm. These cases are considered uncertain, as minor model deviations could affect whether flooding is predicted.

Table 7.2: Difference in centimetres between simulated maximum water level and critical bank level at each location. Green = below critical level, orange = close to critical level (± 2 cm or exceedance 0–10 cm), red = exceedance of critical level.

Scenario	Location							
	A	B	C	D	E	F	G	H
1	-87	-52	-9	-1	1	12	-138	-125
2	-17	-18	18	14	7	13	-87	-125
3	28	11	43	30	14	14	-47	-125
4	-87	-52	-9	-1	1	12	-77	-62
5	-17	-18	18	14	7	13	-50	-62
6	28	11	43	30	14	15	-23	-62
7	-81	-45	-2	7	8	20	1	18
8	-12	-9	28	26	21	28	7	18
9	32	20	53	43	31	32	12	18

7.3.1 Locations A and B

The simulations show that flooding depends on both the location in the river system and the hydraulic conditions applied in each scenario. In the upstream parts of the system, represented by locations A and B, flooding only develops during the highest inflow scenarios, namely 3, 6 and 9. The exceedance is around 30 cm in all cases for location A and ranges from 11 to 20 cm for location B. In all other scenarios, both locations remain below the critical level. This implies that flooding at these upstream locations is primarily driven by river inflow rather than sea level. This is expected, as A and B are the furthest upstream locations in the river system, around 11 km from the downstream sea level boundary.

7.3.2 Locations C and D

Locations C and D respond more clearly to increasing inflow. Location C exceeds the critical level in scenarios 2, 3, 5, 6, 8 and 9 while it remains below in scenario 1, 4 and 7. However, in scenario 7 the difference is only -2 cm, meaning that the simulated water level is close to the critical level. Location D exceeds the critical level in scenarios 2, 3, 5, 6, 7, 8 and 9, and is only 1 cm below in scenarios 1 and 4. This suggests that both C and D reach the flood threshold already under medium inflow conditions. The cases with small differences are particularly important, as they indicate the approximate hydraulic conditions where the transition from no flooding to flooding occurs.

Both C and D appear to be more sensitive to inflow than sea level. This can be seen by comparing scenarios with the same sea level but increasing inflow, where the water level rises substantially from low to medium inflow. In contrast, the change from low to medium sea level has no effect at these locations, as the values in scenarios 1-3 and 4-6 are identical. The highest sea level scenarios, 7-9, do have some effect, especially for location D, where flooding develops even under low inflow in scenario 7. This suggests that C and D are mainly inflow driven, but can still be affected by high sea levels.

7.3.3 Locations E and F

Locations E and F both exceed their critical levels in all scenarios, but their behaviour differs. Location E is close to the critical level in several scenarios. In scenarios 1 and 4, the water level is 1 cm above, and in scenarios 2 and 5 it is 7 cm above. This suggests that location E is already vulnerable under the least severe scenarios, but that the degree of flooding is limited under low and medium conditions. The exceedance increases to +31 cm in scenario 9, showing that the flood risk becomes more severe when high inflow and high sea level occur simultaneously. The results at location E are mainly influenced by inflow. There is no difference between the low and medium sea level scenarios, while the exceedance increases steadily with increasing inflow.

A comparison between locations D and E shows that D increases more rapidly with increasing inflow than E. Although both locations are close to or above, their critical levels under several scenarios, their response to increasing inflow differs. One possible explanation is that location D is more directly affected by increasing discharge, while location E may be more influenced by regulated downstream water levels. Another possible explanation is that the local hydraulic capacity is lower around location D, causing the water level to rise more rapidly when inflow increases.

Location F is affected in all nine scenarios, with exceedance values ranging from 12 to 32 cm. In contrast to location E, the exceedance at F is not small in the lower scenarios. The fact that even the least severe scenario resulted in an exceedance of 12 cm indicates that the critical level at this location is low. Since location F is situated next to a fire station, this result is particularly concerning from a risk perspective. The exceedance is relatively stable under the low and medium sea level scenarios, but increases more clearly when the highest sea level scenario is applied. This suggests that location F is affected by high sea levels as well as inflow.

The difference between locations E and F is also important. Although both exceed the critical level in all scenarios, location E is often only slightly above, while location F is at least 12 cm above. Flooding at E should thus be interpreted as more sensitive to small changes in water level or model uncertainty, whereas flooding at F is a recurring problem. Furthermore, location F is less sensitive to inflow than location E.

7.3.4 Locations G and H

The most downstream locations, G and H, show a different pattern from the other locations. Both remain below the critical level in scenario 1-6, but exceed it in scenario 7-9. This implies that sea level is the dominant flood factor at these locations. This is consistent with their downstream position and their location downstream of the regulating structures.

However, location G is also affected by river inflow, as the exceedance increases from 1 cm in scenario 7 to 12 cm in scenario 9. In contrast, location H has a constant exceedance of 18 cm in scenario 7-9, regardless of inflow. This suggests that location H is mainly controlled by the downstream sea level, while location G is influenced by both sea level and river inflow. One possible explanation is that location G is located

closer to an upstream regulating structure and is therefore more directly affected by its discharge. Another possible explanation is that the majority of the flow passes through Gårda dämme and thus location G, which can be seen in Figure 5.6.

The sea level scenarios used in the simulations represent present day extreme conditions and do not include future sea level rise. However, the projected sea level rise for Gothenburg, ranging from 26 to 64 cm, indicates that the downstream condition may become more critical in the future. This would mainly affect the downstream locations, such as G and H, where the results showed that flooding is primarily controlled by the sea level.

7.4 Temporary storage capacity

The temporary storage capacity was evaluated by closing the regulating structures and allowing the river system to fill from an initial river level of +1 m until the water level at Gårda reached +1.4 m. The purpose was to estimate how long the structures can remain closed under different inflow conditions without exceeding the selected limit upstream of Gårda dämme, and to estimate how much water could be temporarily stored in the river system.

7.4.1 Storage with existing regulating structures

The results for the first storage case, representing the existing regulating structures, are presented in Table 7.3 and Figure 7.16. The available closure time decreased as the inflow increased. At an inflow of 0.3 m³/s, the water level reached +1.4 m after 1440 minutes, corresponding to about 24 hours. At an inflow of 5 m³/s, the corresponding time was reduced to 113 minutes, or just less than two hours.

Table 7.3: Estimated storage volume and maximum closure time for different inflows with existing regulating structures.

Q [m ³ /s]	T [h]	V [m ³]
0.3	24	25920
1	7.3	26340
3	2.7	29340
5	1.9	33900
Mean		28 875

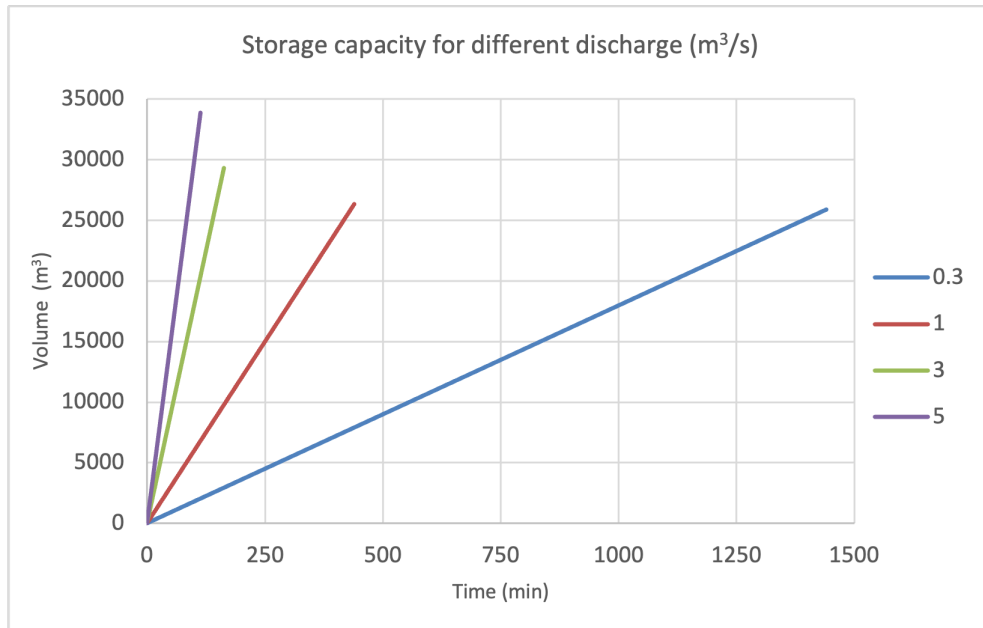


Figure 7.16: Graph showing the storage capacity and time it takes to fill up for different inflows.

The estimated stored volume ranged from around 26 000 m³ to 34 000 m³, with an average of approximately 29 000 m³. The estimated volume therefore varies between inflow cases, even though the same initial and final water levels were used. This implies that the estimated storage volume is not only determined by the available geometric volume between +1 and +1.4 m, but also by how the water level develops along the river during filling.

At higher inflows, the water level gradient along the river becomes more important. Since the control point is located far downstream in the system, it is possible that additional water can be stored in the upstream parts before the river level at Gårda reaches +1.4 m. This may explain why the estimated volume increases with inflow.

7.4.2 Storage with additional regulating structures

A second storage case was investigated to represent a situation where the inner barriers have been built, preventing water from leaving the river system through the outlets to Göta älv, see Figure 3.18. The results are shown in Table 7.4 and Figure 7.17. The maximum closure times increased significantly for all inflow conditions. For an inflow of 0.3 m³/s the water level reached +1.4 m after 4020 minutes, corresponding to 67 hours. For an inflow of 5 m³/s, time was 285 minutes, or 4.75 hours.

Table 7.4: Storage capacity between 1.0 m and 1.4 m with the additional inner barriers.

Q [m ³ /s]	T [h]	V [m ³]
0.3	67	72 360
1	20.5	73 800
3	7.3	78 300
5	4.8	85 500
Mean		77 490

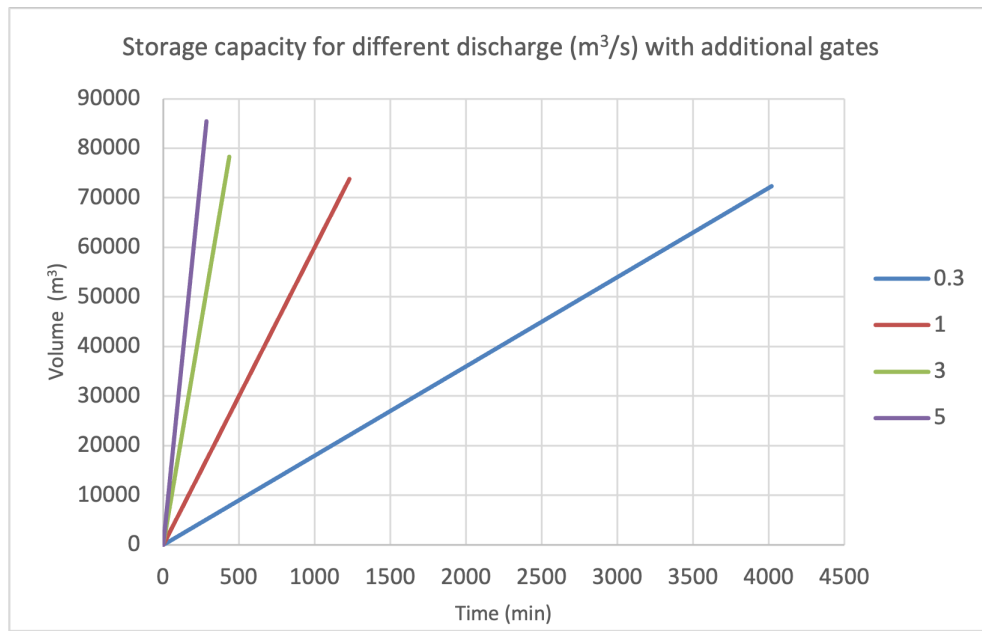


Figure 7.17: Estimated storage volume and maximum closure time for different inflows with additional inner barriers.

The estimated stored volume for this case ranged from approximately 72 000 m³ to 86 000 m³, with an average of 78 000 m³. This is around 2.7 times larger than in the first case. This result shows that the inner barriers could significantly increase both the temporary storage capacity and the available closure time.

7.4.3 Comparison with previous research

The storage volume calculated in this thesis can also be compared with results from a previous study by Sweco, presented in Section 3.6.1. In that report, two storage capacities were estimated, one with closure at Slussen and the culverts in Gullbergsån, and one with closure at the inner barriers. The first, smaller storage volume is difficult to compare directly with the results of this thesis, since the closing structures are not located in the same positions.

The second, larger volume is more suitable for comparison, as its closing structures are located at the same positions as in this thesis. The Sweco report, however, based its

estimate on a water level increase from +1.0 m to +2.0 m, while this thesis considers a smaller increase from +1 m to +1.4 m. To make a simplified comparison, a linear relationship between water level increase and storage volume was assumed. Based on this assumption, Sweco's estimate of 195 000 m³ corresponds to around 78 000 m³ for a water level increase of 0.4 m, which is the same as the volume result in this thesis.

The close agreement between the estimates is positive, but it can not be used as a direct validation of the calculated storage. This is because the comparison is based on a simplified assumption, and the method behind Sweco's estimate is not analysed in detail. The comparison should therefore primarily be interpreted as an indication that the two estimates are of similar magnitude.

7.4.4 Comparison between storm durations and maximum closure times

The storage results were also compared with the high sea level duration analysis in order to evaluate whether temporary closure could be effective during periods of high sea level. Figure 7.18 presents the cumulative distribution of high sea level durations together with the maximum closure times for different inflow conditions. The second storage case with an inflow of 0.3 m³/s is not included in the figure, since the closure time is more than twice as long as the longest identified storm duration.

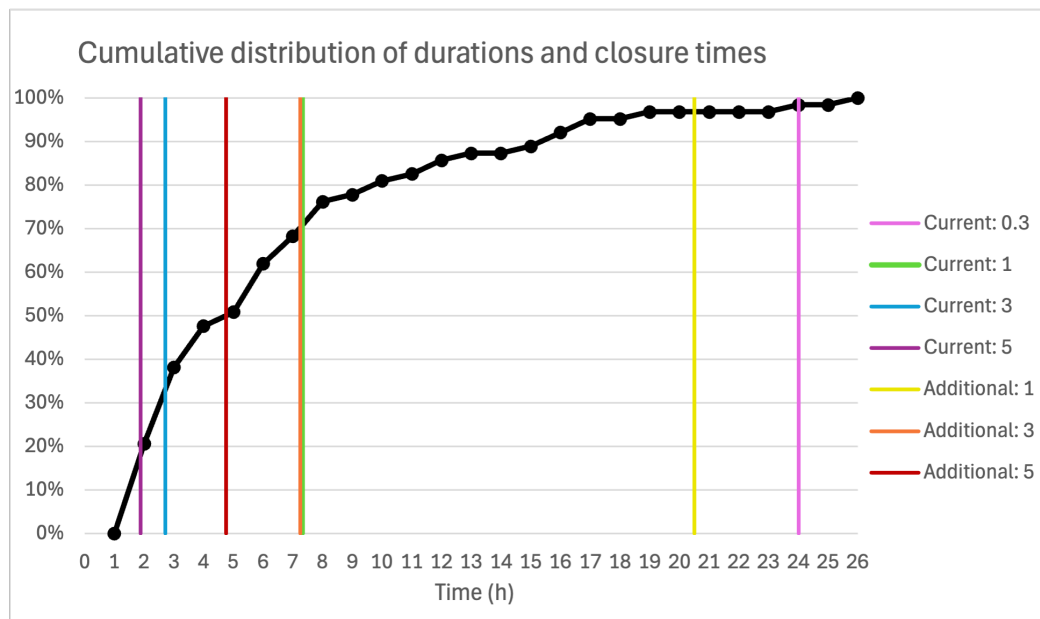


Figure 7.18: Cumulative distribution of sea level durations compared with maximum closure times for different inflow conditions.

For existing regulating structures, the result implies that the maximum closure time is sufficient for almost all identified events when the inflow is 0.3 m³/s. At higher inflows, the percentage of events shorter than the maximum closure time decreases. At an inflow of 1 m³/s, approximately 70% of the events are shorter, while the corresponding share is around 30% for 3 m³/s and around 20% for 5 m³/s.

For the second storage case, the maximum closure time is longer for all inflow conditions. At an inflow of $1 \text{ m}^3/\text{s}$, the maximum closure time exceeds the duration of approximately 95% of the identified events. At $3 \text{ m}^3/\text{s}$, the corresponding share is around 70%, and at $5 \text{ m}^3/\text{s}$ it is around 50%. This shows that the additional inner barriers could make temporary closure effective for a large proportion of extreme sea level events, particularly under low to moderate inflow conditions.

The storage analysis assumes that the inflow to the downstream part of Mölndalsån can be kept approximately constant during a high sea level event. This is considered a reasonable assumption since most of the inflow is regulated by the lakes upstream. The main uncontrolled contribution is Källeredsbäcken, but its flow is small compared with the tested inflow scenarios. However, a limitation is that direct precipitation and local runoff are not included. These contributions could increase the inflow during an event and thereby reduce the possible closure time.

Furthermore, the high sea level periods were treated as separate events, even though some may originate from the same storm. This was considered acceptable because the gap between consecutive peaks was at least five hours. This interval was assumed to be sufficient to release the accumulated water before the next high sea level peak. The assumption is supported by the study presented in Section 3.6.1 where pre-release of the river was estimated to require approximately 2-6 hours.

7.5 Recommendations for flood mitigation

This section presents recommendations for flood mitigation in Mölndalsån based on the identified flood patterns. The recommendations are divided into two parts, one focusing on the different sections of the river system, and one on how temporary storage could be used during periods of elevated sea level.

7.5.1 Mitigation by river section

Effective flood mitigation in Mölndalsån requires coordination between the regulating structures, since operational decisions at one structure can influence water levels and discharge conditions elsewhere in the system. The simulations show that different mitigation measures are relevant for different parts of the river system, depending on whether flooding is mainly caused by river inflow, sea level, or a combination of both.

For locations A, B, C and D, where flooding is mainly inflow driven, discharge from the upstream lakes is important. Reducing or delaying the discharge during crucial periods could lower the water levels in the downstream parts of the system. This requires coordinated regulation of the upstream lakes and downstream structures, and using forecasts to pre release water before events in which high inflow and elevated sea levels are expected to coincide.

For locations G and H, where flooding is mostly controlled by sea level, construction of the inner barriers would likely be more effective. Locations E and F are affected by

both inflow and sea level, and therefore require a combination of mitigation measures. Location F is especially vulnerable, since flooding occurs even in the least severe scenarios. Since this location is close to Gårda dämme, it may be relevant to investigate whether a lower operational target level upstream of Gårda dämme could be beneficial.

7.5.2 Utilising the temporary storage

The temporary storage analysis indicates that the existing regulation strategy could also be used more actively during high sea level events. By lowering the water level in advance to +1 m and then closing the structures during the peak of a storm surge, the river system could temporarily store incoming water while limiting the influence of high sea levels. This type of operation is similar in principle to storm surge barriers such as the Thames Barrier and the IJssel Barrier, discussed in Section 3.7.

A possible strategy would be to temporarily lower the operational target level to +1.0 m before an expected high sea level event, allowing the river level to decrease before the storm peak occurs. Closure of the structures could then be initiated when the sea level approaches the river level at approximately +1.0 m. The structures would remain closed during the storm peak and could be reopened when the water levels on both sides are approximately equal. When reopening, the structures could return to normal operation. This would reduce the risk of high sea levels propagating upstream.

This strategy differs from the method described in Section 3.6.1, where the water level is lowered manually to +1.0 m without changing the operational target level. Manual lowering can also create temporary storage in advance, but its effectiveness depends on the timing. The time required to lower the river level depends on the inflow, meaning that high inflow conditions may require a longer preparation time or may limit how much the level can be reduced before the storm arrives. In contrast, a temporary change in operational target level could provide a more controlled way of creating storage before a forecasted event.

However, this type of operation would require reliable sea level forecasts and clear operational thresholds. Although sea level forecasts are available from SMHI, further work would be needed to determine how such forecasts could be implemented in the operation of the regulating structures. Since gate operations, such as closing and reopening, may take time, decisions would need to be made beforehand. It should therefore be investigated which forecasted sea level should prompt this alternative operation, and how much preparation time would be needed.

If storm duration, precipitation and sea levels increase in the future due to climate change, the available storage time may become insufficient during some events. In that case, pumps at the regulating structures could be investigated as a complementary mitigation. This would allow the water to be discharged from the river system even while the structures remain closed against high sea levels.

8 General discussion

This section discusses the main uncertainties and limitations of the study and how they may affect the interpretation of the results. It also presents suggestions for future work to improve the analysis of flood risk along Mölndalsån.

8.1 Uncertainties

Several uncertainties should be considered when interpreting the results. One source of uncertainty is the accuracy of the input data, especially the flow and water level data for Mölndalsån. The sea level data covers several decades, has hourly measurements and has been quality controlled, and is therefore considered relatively reliable. In contrast, the available data for Mölndalsån contains periods of missing data and is available as daily averages. This limits the possibility of analysing short term variations in flow and water level.

Some inconsistencies were also observed when comparing flow measurements along Mölndalsån. On some days, the downstream flow was larger than the upstream flow, which may be explained by local inflow from precipitation and runoff. However, on other days the downstream flow was smaller, even though there are no major outlets between the two measuring stations. This suggests that some of the flow measurements may contain errors. Possible causes include measurement errors, local disturbances or debris affecting the measurement equipment. The water level measurements are assumed to be more reliable, since it is generally easier to measure than discharge.

Minor instability was also observed in the model around the regulating structures. When the water level reached the operational level, the gates opened, which caused the water level to decrease rapidly. This then caused the gates to close again, creating an oscillating pattern. For higher flows, the oscillation stabilised relatively quickly, while for lower flows it continued for a longer period. In cases where the model did not fully stabilise, the mean value of the oscillations was used. This introduces uncertainty in the simulated levels, especially in scenarios where the simulated level was close to the critical bank level.

The use of steady state scenarios is another limitation. Constant inflow and sea level conditions were used to distinguish between the effects of different hydraulic conditions in a controlled way. However, real flood events are dynamic, and both river inflow and sea level vary over time. The timing between peak inflow and peak sea level may therefore influence the actual flood risk in reality.

There is also uncertainty related to the sea level boundary condition. The sea level scenarios were based on measurements from a station located closer to the coast, while the study area is located further upstream in Göta älv. Previous studies indicate

that water levels during storm conditions may differ between these locations. This means that the sea level applied in the model may not fully represent the water level at the outlet from Mölndalsån, and the return period of the sea level scenarios should therefore be interpreted with caution.

Finally, the temporary storage analysis is based on simplified assumptions. Surface runoff, direct precipitation and local inflows were not included in the simulations. During high sea level events, these contributions could increase the inflow to the river system and reduce the available closure time. The calculated storage capacity and maximum closure times should therefore be interpreted as estimates under perfect conditions rather than exact operational limits.

8.2 Future work

Future work could include simulations using unsteady inflow and sea level data from real events. This would allow the effect of timing between peak discharge and peak sea level to be analysed in more detail. It would also be relevant to estimate the return period of compound events in order to better understand how often it may occur.

Future studies should also consider local runoff and direct precipitation during high sea level events. These contributions were not included in the storage analysis, but could increase the inflow to the river system and reduce the available closure time. Furthermore, future climate scenarios with projected sea levels and river inflow could be applied to assess how the situation may change over time.

A two dimensional flood model could be used to analyse the flood extent across surrounding areas in more detail. This would provide a better understanding of flow paths and affected infrastructure once the river banks are overtopped. It could also improve the communication of flood risk to the wider public, which may support preparedness and planning.

9 Conclusions

This thesis investigated flood risk in Mölndalsån using a one dimensional hydraulic model. The simulations show that flood risk varies along the river system and depends on the interaction between river inflow, downstream sea level and hydraulic regulation. The results are strongly linked to the regulated water levels at Gårda dämme and Slussen, which limit the influence of downstream sea levels except during especially high conditions. The upstream part was mainly affected by river inflow, the most downstream by sea level, and the central locations by both factors.

The scenario simulations showed that flooding may occur at several of the selected locations. Locations A and B only exceeded their critical bank levels during the highest inflow scenarios, while locations C and D reached their critical levels already under medium inflow conditions. Locations E and F exceeded their critical levels in all scenarios, although the difference at E was often small and therefore more sensitive to model uncertainty. Location F was identified as particularly vulnerable, as flooding developed even in the least severe scenario and the location is situated close to a fire station. The downstream locations G and H were predominantly affected by high sea level, with flooding occurring only during the highest conditions.

The results indicate that flood mitigation in Mölndalsån requires different strategies in different parts of the system. In the upstream and central sections, regulation of discharge from the upstream lakes is important during high inflow conditions, while additional inner barriers could be more effective in the downstream part. For locations affected by both inflow and sea level, coordinated regulation of upstream and downstream structures is needed.

The temporary storage analysis showed that the river system can provide storage during periods of high sea level if the regulating structures are closed. With the existing structures, the maximum closure time decreased with increasing inflow. When additional downstream regulation was included, both the maximum closure time and the estimated storage volume increased, suggesting that inner barriers could improve the potential for temporary storage. Comparison with high sea level durations showed that temporary closure could be effective, particularly under low inflow conditions. However, the effectiveness decreases during higher inflow and longer durations of high sea levels. The storage results should thus be interpreted as an indication of potential capacity, since local runoff, direct precipitation and unsteady scenarios were not included.

Overall, the study shows that flood risk in Mölndalsån is strongly influenced by hydraulic regulation and cannot be assessed from river inflow or sea level alone. The results emphasise the importance of considering the river system as a whole, where measures in one part may affect flood risk in another. This is particularly relevant for future flood risk management, as rising sea levels may increase the need for coordinated regulation and additional storage capacity.

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