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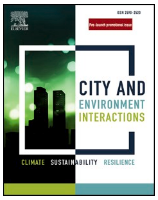

A methodology for the assessment of compound sea level and rainfall impact on urban drainage networks in a coastal city under climate change

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ABSTRACT

This study seeks to investigate how stormwater drainage systems in coastal cities respond to climate change in terms of simultaneous sea level rise and rainfall. 7.5 years of recorded rainfall and sea level data in the city of Trelleborg in Sweden were used to generate projections of future climate events based on the emission scenario RCP8.5. Twelve scenarios were formulated to represent rain and sea level in today's (reference)- and future climate. Future rainfall was computed using regional climate model data together with the Delta Change Method. Sea-related data was represented with two variables, namely an average sea level and storm surges. The average sea level was calculated to reflect seasonal variation using a second-order Fourier analysis whilst raw gauge data was used to capture the storm surges. The two sea variables were then scaled to represent future projections of sea level rise and storm surges in the study area. The performance of the drainage system was simulated with MIKE Urban 1D model and the results were expressed through two indicators, *number of flooded nodes* and *flood frequency*. The results of this study reveal a tipping point is likely to be found between years 2075 and 2100, after which storm surges become a major driver for overwhelmed drainage system. It was also found that pluvial floods may become more likely and frequent during winters as time progresses. This has a great implication when deciding on adaptation measures.

Introduction

On a global scale, the direct link between anthropogenic greenhouse gas emission and daily weather has recently been demonstrated by Sippel et al. [1], inferring that climate change is occurring here and now. As a result of man-induced climate change, an increase in precipitation intensity and altering rain patterns are to be expected in the near future [2], hence elevated risk of *pluvial flooding* [3].

Climate change does not only impact the behavior of precipitation, but also causes deglaciation and thermal expansion in the World Ocean. These are influential factors partially explaining the observed increase in the global mean sea level (GMSL). The rise in GMSL puts coastal cities and their hundreds of millions of residents at flood risk worldwide. *Coastal flooding* due to storm surges induced by high wind velocities pushing sea water into the cities can be detrimental and catastrophic. Co-occurrence of sea-level rise and storm surges (coastal flooding) with rainfalls (pluvial flooding) leads to challenging flood management in coastal areas around the world and Sweden is no exception [4,5]. Only in 2013, four strong storms struck Sweden of which two storms, i.e., Simone 27th–28th October 2013 and Sven 5th–7th of December 2013, occurred in the Öresund region—where Malmö, Helsingborg and Copenhagen are located—causing damages to an equivalent of approximately €630 million in Sweden and Denmark collectively [6]. It is worth mentioning that according to reports, the newly constructed subway system of Malmö at the time survived the storm surge by just a 2-decimeter margin [7]. Only 8 months later, on the 31st of August 2014, Malmö experienced another catastrophic climate event, namely an exceptional cloudburst pouring 100 mm of rain in less than 4 h. The event led to extensive inundations throughout Malmö causing enormous economic damage [6,8,9].

Considering the fact that the isostatic uplift in southern Sweden is close to zero [10], future scenarios of combined sea-level rise and torrential rainfall events, causing compound flooding, are deemed crucial to be studied due to severity of such catastrophic events [11–13]. In other words, if rain together with sea induce more severe flooding, new strategies need to be developed to cope with the future.

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The number of studies describing how climate change will impact urban areas in the future are abundant. However, published literature reveals that many studies mainly focus on sea- and rain variables separately to express the effect of climate change [14–22], while assessments combining these two climate phenomena to evaluate the resilience of urban drainage systems has not been comprehensively studied. Nevertheless, Domingo et al. [18] demonstrate that storm surges, with or without sea-level rise, lead to seawater propagating into the pipe system in coastal cities resulting in flooding. Knowing that downstream hydraulic head can severely affect the performance of a pipe system, investigating the urban drainage system in the perspective of outlet hydrodynamics is important.

With increased sea levels, more backwater is likely to end up in coastal pipe systems. It is therefore important to study possible scenarios and dynamics to be able to plan feasible actions to avoid urban drainage failure. Doing so, one needs to account for the different processes impacting sea-level rise. The first driver contributing to local sea-level rise descends from the observed increase in GMSL. The second aspect deals with phenomena occurring on a regional scale, wherein several processes can be described, such as *changes in land-ice mass and in land–water storage*, *fresh water addition from melting glaciers and changes in the distribution of heat*, *tectonics and sediment compaction*, and *glacial isostatic adjustment* [23,24]. Focusing on the Baltic Sea, one needs to pay attention to atmospheric pressure and wind stress. Together they induce storm surges which, based on empirical data, can bring sea levels up to two meters above normal state [25]. As GMSL rise and storm surges differ in terms of temporal resolution, varying between years-centuries and minutes-days respectively, they affect coastal cities differently [23].

Intensive precipitation and storm surges have historically not occurred during the same season in Sweden. Intensive rainfalls have mostly been a summer event [26,27] whilst storm surges have appeared in autumn- and winter seasons [25,28]. Therefore, the risk of urban drainage failure in Sweden due to cooccurring events was discarded. However, since the stationarity of climatic phenomena has been questioned [29,30] and deterministic design practices need to be substituted with probabilistic (risk-based) approaches [31], such an assumption has to be revisited for future settings [13,32,33].

Different methods are available for the assessment of urban drainage systems, including the choice of modelling tool and performance indicators. In a Nordic context, the MIKE products powered by DHI (Danish Hydrological Institute) are commonly used to investigate the hydrodynamic behavior of urban drainage systems. However, there is no widely accepted methodology regarding how available measured data of sea-level and rainfall could be concurrently used in available modelling platforms to assess urban drainage.

The aim of this paper is therefore to develop a methodology, through a case study, for assessing the performance of drainage systems in coastal cities under simultaneous impacts of both sea-level and rainfall alterations due to climate change. The study uses long-term measurement data for hydrodynamic modelling to assess the impact of rainfall and sea level on the drainage system in today's (i.e., reference)- and future climate.

Data and methods

Case study

The coastal city of Trelleborg, situated in the very most southern part of Sweden, is currently trying to deal with potential flooding issues due to rising sea levels. As Trelleborg plans to establish a new development area along the coastline, extra effort to attenuate the effects from a potential GMSL rise is essential.

In Trelleborg, Kuststad 2025 (Coast-city 2025) is an extensive urban development project that involves investments in business, infrastructure to accommodate over 4000 new homes in a location close to the sea. The project develops Trelleborg's potential, utilizes the municipality's strategic location and takes a holistic approach for the city to regain contact with the sea.

During the preparation of the thematic description for Kuststad 2025, several new investigations are required to be made to support completed and ongoing work. In addition, the investigations are needed to be able to answer specific questions in accordance with legal requirements, including a general risk investigation regarding climate change and environmental impact assessments. Furthermore, the County Administrative Board considers that the coastal protection investigation carried out for the city of Trelleborg in 2017 should be supplemented with a description of protection against high sea levels for a longer time perspective than until 2100, and with an analysis of flood risk when torrential rain and high sea levels occur simultaneously (compound impacts). Therefore, the city of Trelleborg needs a methodology to be able to implement and meet the requirements set for the city before the launch of Kuststad 2025.

Today, Trelleborg is using a conventional separate pipe system to transport stormwater away from the urban environment to a recipient, namely the sea. The stormwater pipe system in western Trelleborg collects runoff from different sub-catchments (Fig. 1). The largest drainage area (The Green catchment) is directly connected to the sea, whilst the smaller catchment (color-coded in yellow) diverts stormwater to the ocean through the Green pipe network. The joint drainage area covers a region of 478 ha (369 ha Green and 109 ha Yellow), where most of the land is used as residential areas. The ground elevation varies between 0 and 25 m above sea level. Stormwater pipes are made from concrete and the longest pipeline stretches roughly 4 km with pipe diameters ranging from 0.15 m to1.4 m.

Method development

Data acquisition and projections

Rainfall. The rain gauge (Model: *Adcon Professional Rain Gauge*, ID: *Engelbrektsgatan Borra 1038*) in Trelleborg is a tipping bucket capable of reading precipitation data with 0.2 mm volumetric resolution. This data was translated into a continuous 7.5-year rainfall dataset (2012/04–2019/09) with a one-minute resolution. Correcting for future rain series involved the usage of the *Delta Change method*. In contrast to Camici et al. [34] which uses a monthly changing factor, this study applied a seasonal factor. Utilizing a seasonal factor allows for assessing whether rainfall together with sea-level rise will impact the urban drainage system in the future. On the other hand, seasonal changing factors could lead to an oversimplification of rain projections which in turn might overlook accurate intensities in the future. For instance, a reduced amount of summer rain does not necessarily mean lower summer intensities in the future [17]. However, as the purpose of the current study is to investigate whether sea-level rise is worth considering in future assessments, seasonal factors are thought to serve such purpose.

The seasonal factors used in this study (shown in Table 1) are based on an ensemble analysis using RCA4, a regional climate model (RCM), developed at Rossby Centre in the Swedish Meteorological and Hydrologic Institute (SMHI). RCM dynamically downscales data from nine different global climate models/general circulation models (GCMs) [35]. As a result, a multi-model mean was calculated using RCA4 data with 50 × 50 km resolution. Table 1 presents the changing factors for southern Scania, wherein Trelleborg is located.

The Delta change method in Eq. (1) finds a linear relationship between the observed precipitation data (P_{OBS_k}) and the projected time series ($P^{fut}_{OBS_{k,DC}}$) using a changing factor (δ_k).

$$P^{fut}_{OBS_{k,DC}} = P_{OBS_k} \bullet \delta_k \qquad k = 1, 2, 3, 4 \tag{1}$$

where k represents each season in a temperate climate. This statistical downscaling operation yields four unique rain series, one observed and

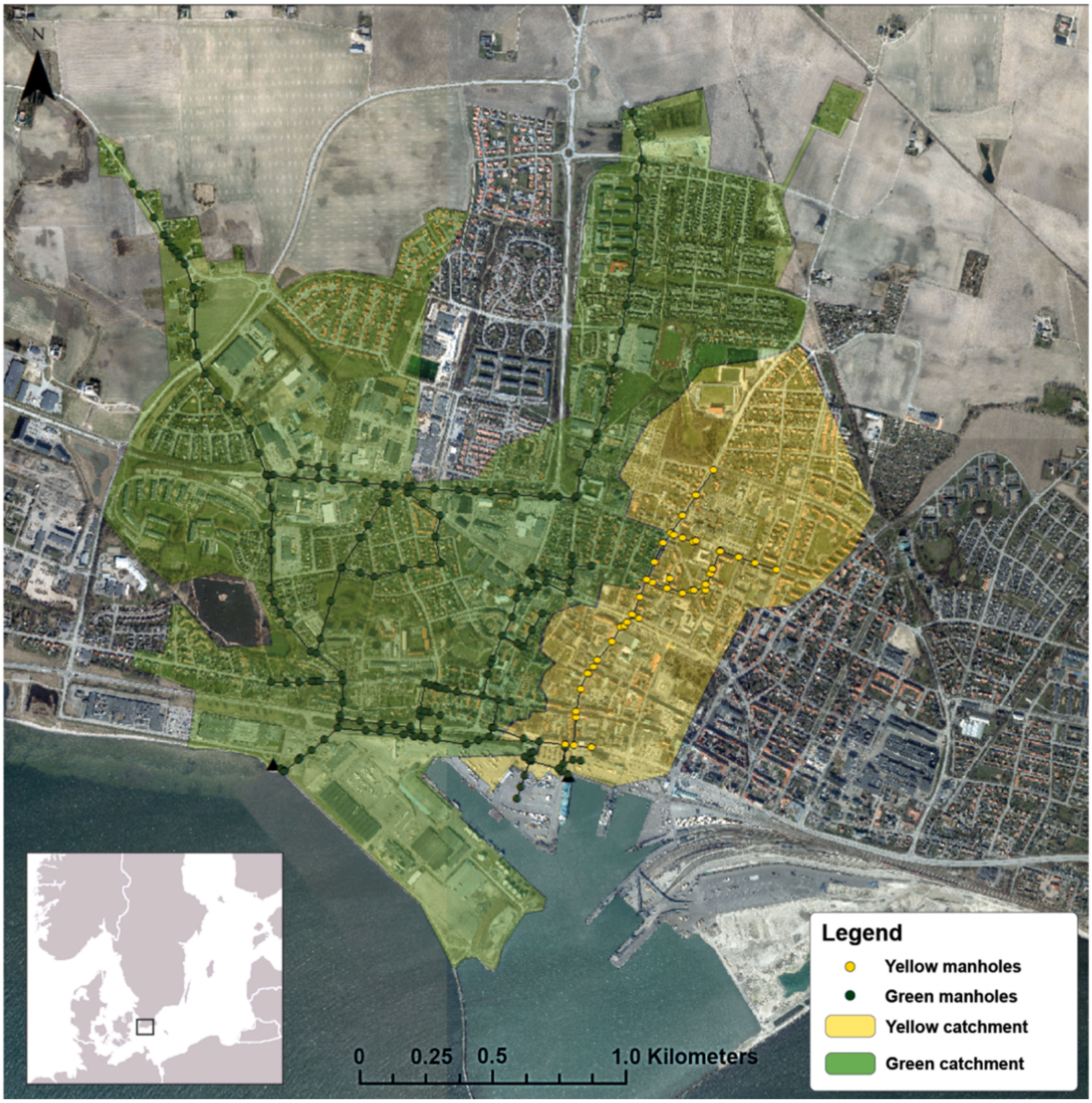

Fig. 1. The drainage area of western Trelleborg, location 55.3762° N, 13.1474° E reference system WSG84. Two sub-catchments (color coded green and yellow) are presented. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

three projected (Fig. 2). Each of them varying in seasonal precipitation as the changing factor depends on both the season and the time frame. Note that due to the fine temporal resolution of Fig. 2 dry spells are not properly presented.

Sea-level. The hydrodynamics of the Baltic Sea varies along the Swedish coastline, explaining why it is important to recognize the coastal location of Trelleborg. A survey attempting to group Swedish coastlines based on similar sea characteristics discloses that Trelleborg belongs to the stretch of the Southern Baltic Sea [36]. Since no suitable data is available for Trelleborg, one needs to turn to other stations. This gap was filled by Nerheim [37] which analyzed the covariance for nearby stations in the Southern Baltic Sea to find a suitable replacement for Trelleborg (Fig. 3). Since the result showed a strong link between the stations in *Ystad*, *Skanör*, *Simrishamn*, and *Klagshamn*, the station in Skanör (closest to Trelleborg) was used to retrieve measurements representing the sea level fluctuations in Trelleborg harbor.

Hourly data (Fig. 4a) was employed in this study as it captures sea level- and backwater variation in the system most efficiently. While coarser resolution loses sea level variation, finer data increases the computational demand drastically. In addition, sub-hourly oscillations are negligible considering the scope of the current study. The simulation period corresponds to the runtime of the precipitation series, which is 2012/04–2019/09.

The projected sea levels for Skanör for 2050, 2075 and 2100, obtained from Nerheim et al. [38], are presented in Table 2. No changes in sea dynamics were considered when correcting for future series (Fig. 4b, 4c, 4d). Also, tides in the Baltic sea are trivial, explaining why no further effort was made to consider this effect [25].

Table 1
Changing factors valid for the catchment areas of Nybro-, Sege-, Höje-, Kävlinge-, Sax- and Rå river, Sweden. The projected precipitation change is based on a multi-model mean calculation under emission scenario RCP8.5.

Season	$\delta_k(2050)$	$\delta_k(2075)$	$\delta_k(2100)$
Spring	1.13	1.12	1.33*
Summer	0.94	1.11	0.97*
Autumn	1.05	1.08	1.17*
Winter	1.28	1.26	1.57*

[*] An ensemble of eight GCMs. No data available for the GCM MOHC-HadGEM2-ES.

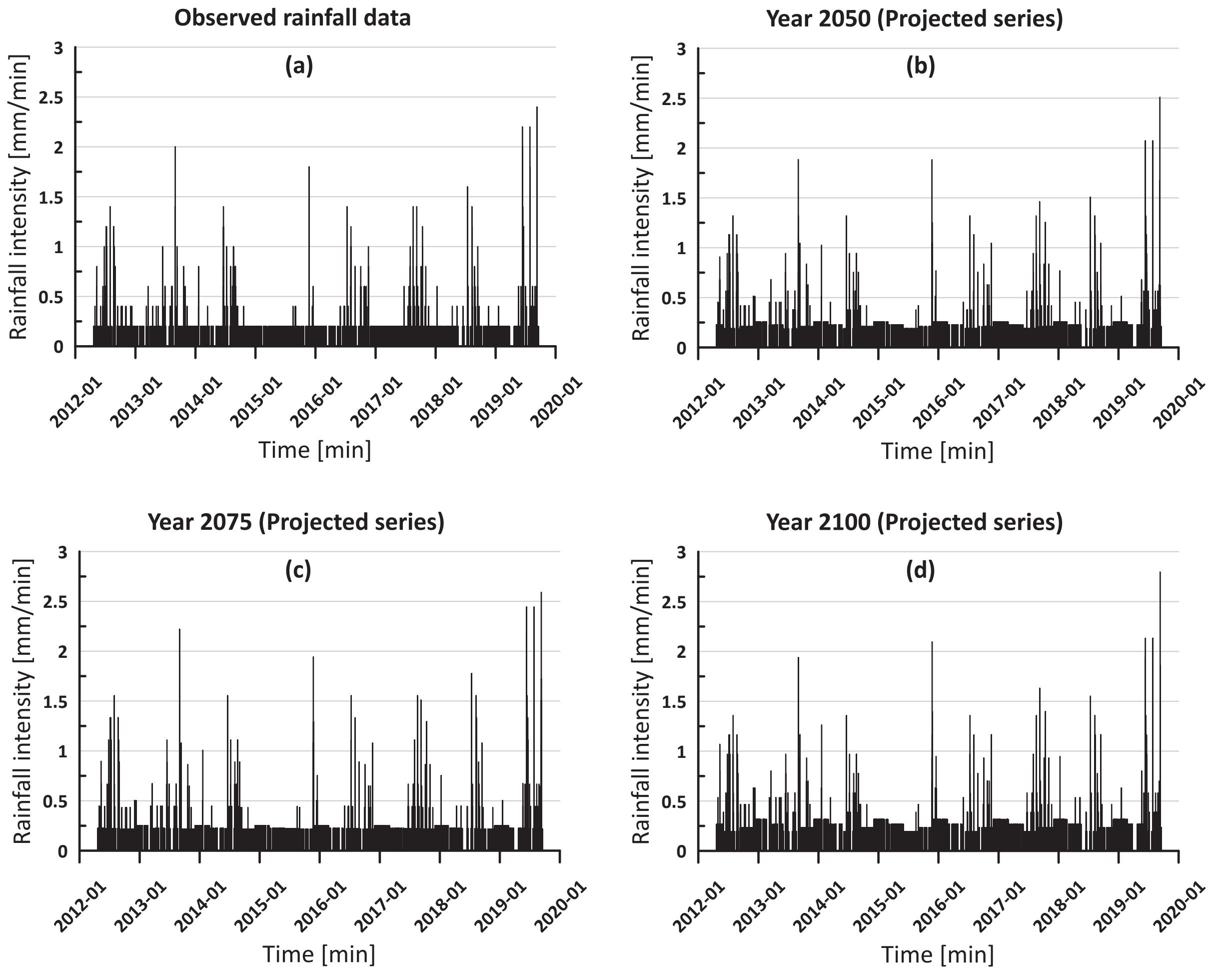

Fig. 2. The observed rain series and the projected rain series for the years 2050, 2075 and 2100. The time step for all series is one minute.

From what has been observed, the average sea level in the Baltic Sea fluctuates on a seasonal basis. Even though the magnitude of the amplitude differs between the stations, a mutual trend showing a minimum in spring- and maximum in autumn/winter has been established [39,40]. The raw sea level data presented in Fig. 4a acquired from SMHI was processed to obtain a mean value for each month yielding the annual average sea-level cycle. The twelve mean values were then used as inputs for a second-order Fourier analysis using MATLAB. The Fourier model was thereafter applied to generate an hourly time series describing the annual behavior of the average sea level in Trelleborg (Fig. 5a). The acquired pattern was then replicated in the projected average sea level scenarios adjusted according to Table 2 (Fig. 5b).

Scenario development. The timeframe of this study extends to the year 2100. Twelve scenarios were developed to investigate how the pipe system responds to climate change through time. As seen in Table 3, four time periods are described, including the present state, the year 2050, 2075 and 2100. Moreover, scenarios 1–8 were formulated to represent the combined effect of rain and average sea level/storm surges. On the other hand, scenario 9–12 were created with the aim to differentiate the two stressors, i.e., rainfall and sea level rise. Hence, different stressors can be pinpointed.

Modelling approach

Multiple scenarios according to Table 3 are fed into the MIKE Urban model, generating answers describing the stormwater system performance. The result is expressed through two performance indicators, namely the *number of flooded nodes* (NFN) and *flood frequency* (FF). Finally, the analysis focuses on how these indicators depict the functionality of the system in terms of spatial- and temporal variation. The relative impact of sea and rain is also assessed. The physical drainage system was translated into a MIKE Urban model. This included defining the catchment area and land use types, as well as outlining the existing pipe network. The model was further developed to meet the needs of the current study, as follows.

When testing the performance of the pipe system in MIKE Urban, the complexity of the model needs to be regarded due to deficiency in computer capacity. A trade-off between the size of the network file and input data is thus necessary. Since the novelty of this study relates to investigating the interaction between sea level and rainfall episodes, the emphasis lies in persevering the quality of the continuous inputs. The drainage network was therefore stripped of branch pipes.

As the case study is divided into two areas (Green and Yellow as shown in Fig. 1), the catchments were modelled separately to maintain model complexity. The largest drainage area (the Green catchment) is of the highest interest as it is directly discharged into the sea. The smaller catchment (the Yellow catchment) was simulated separately, and the calculated flow series was introduced to the Green system as a boundary condition through the interfacial/connecting node. Subsequently, the main model accounted for the boundary condition; rainfall, average sea-/storm level and water flux leaving the Yellow drainage area.

The Green system comprises 190 manholes and two outlets (Fig. 1). In addition, it was assumed that the urban land cover (land use distribution) remains unchanged throughout the study timeframe to confine the study to the impact of climate change, although it is known that land

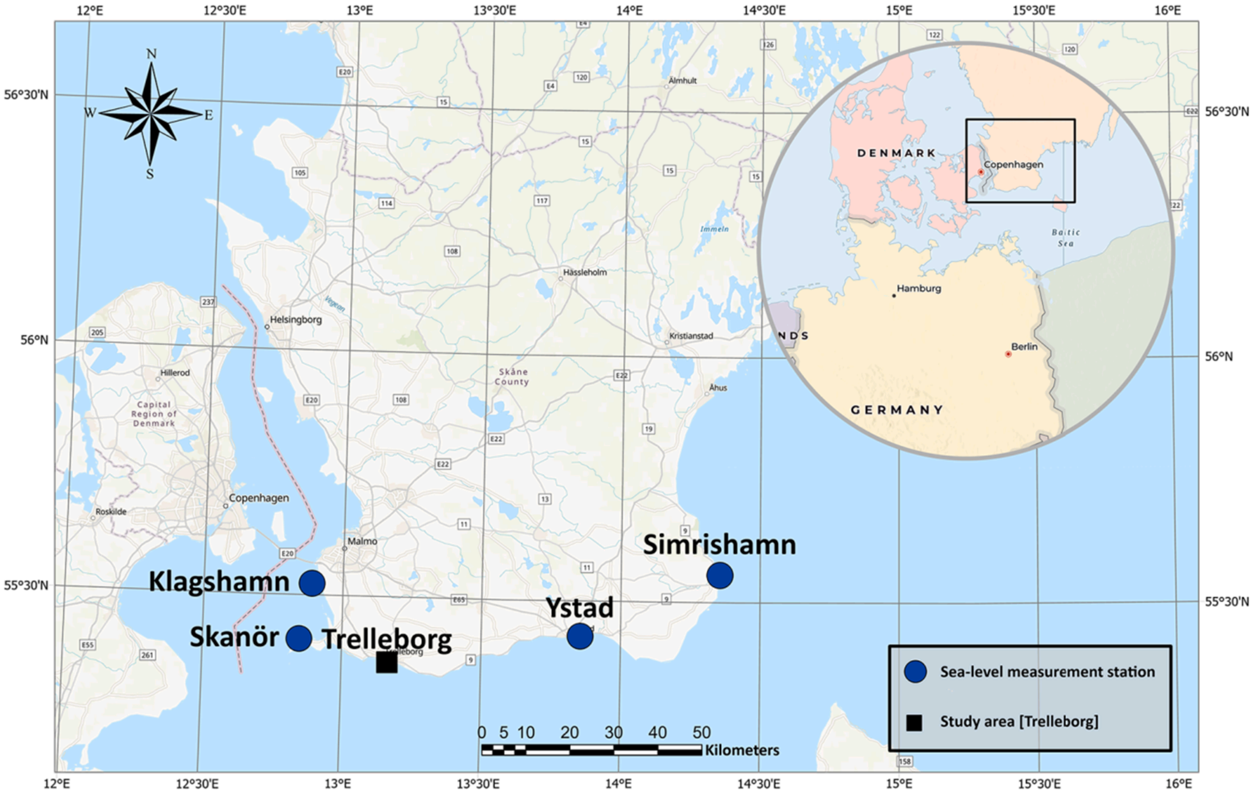

Fig. 3. Sea-level measurement stations included in Nerheim [37]. The location of Trelleborg is also presented.

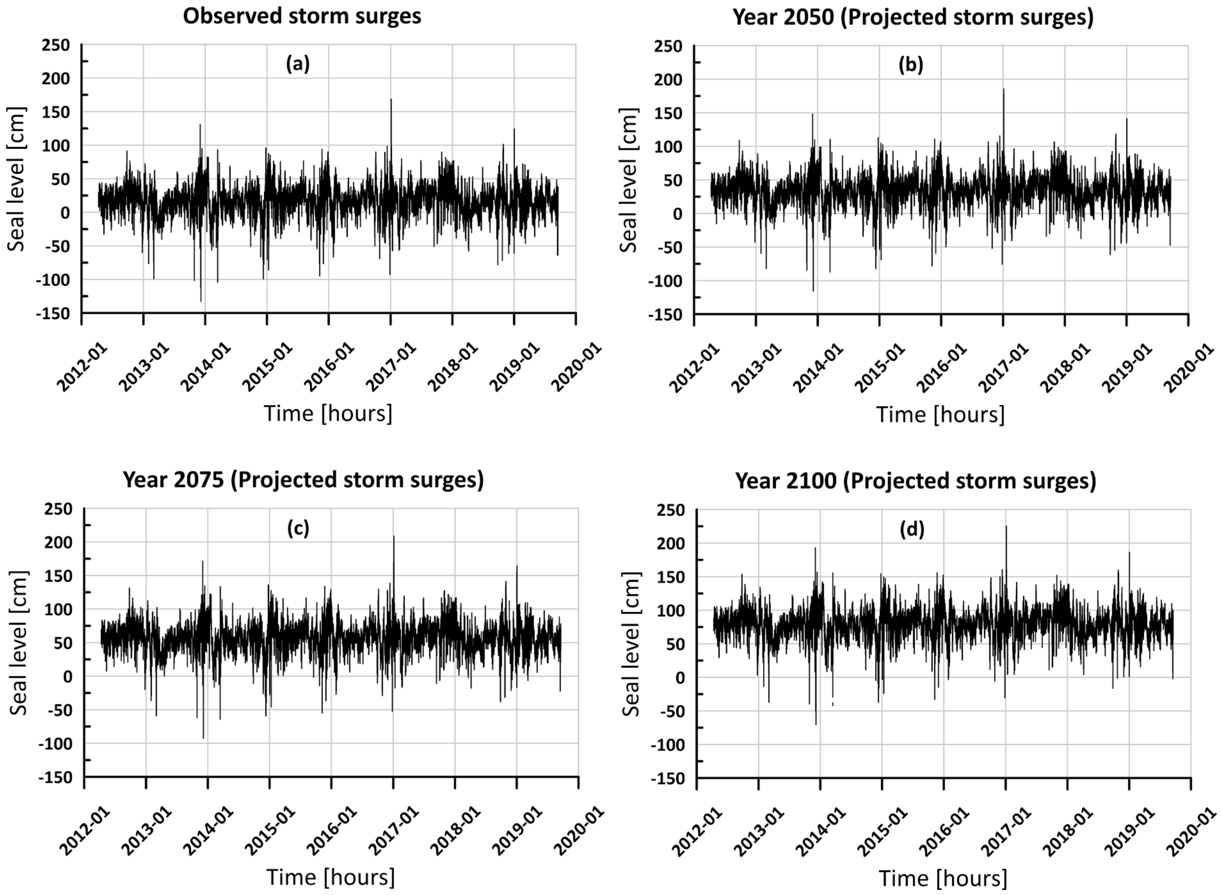

Fig. 4. The storm input representing the present state and the projected years 2050, 2075 and 2100 (reference system RH2000). The time step resolution is one hour.

Table 2

Today's and projected average sea levels in Skanör in the year 2050, 2075 and 2100, expressed in cm (reference system RH2000). Isostatic uplift is considered, and the sea levels are computed under emission scenario RCP 8.5 [38].

	Today	2050	2075*	2100
Skanör (Sea level)	+16 cm	+33 cm	+56 cm	+78 cm

* An interpolation was made for year 2075 since no record was found for this projection.

use changes over time and contributes to the increased urban flood risk [3,41]. Runoff coefficients for MIKE Urban subcatchments were determined using guidelines provided by the Swedish Water and Wastewater Association [42]. The model was neither calibrated nor validated due to the lack of resources. However, the calibration was not assessed essential considering the comparative nature of this study, in which the change between today's and future urban drainage performance is in focus, yielding a negligible relative error.

Results

Fig. 6 presents the model results describing drainage failure due to the combined effect of rainfall and average sea level/storm surges (*Scenarios 1–12*), expressed as NFN and FF respectively. It should be emphasized that Fig. 6a and 6b display the results from a simulation treated as one run. In other words, the indicator NFN describes if a node is flooded or not during a 7.5-year period, independently of the rate of recurrence. The FF-indicator is determined by counting how many flood incidents that occurred during the simulation period.

The NFN and FF presented in Fig. 6a and 6b imply that today storm surges and average sea level have comparable impacts on the resulted flooding events. However, the NFN calculated for future scenarios suggests that average sea level might gradually become the slightly stronger driving force in the sea-induced flooding of the coastal urban drainage network, although the dominance is not tangible. The FF- indicator shows that storm surges—although insignificant in terms of drainage failure up to 2050—gain an increasing importance, from 2050 onwards, compared to average sea level in the estimated flood frequency with an abrupt jump caused in between 2075 and 2100. This implies that the average sea level and storm surges combined with rainfall have a similar impact on the drainage system up until around 2075, after which storm surges and rainfall introduce a severe flood risk to the drainage area. It should be noted that in general, scenarios representing only rainfall show milder impacts with regards to both NFN and FF (*Scenarios 9–12*).

Spatial variation (NFN and FF)

The spatial variation of flooding was simulated during a 7.5-year period. Fig. 7 shows where the flooding occurs (red nodes) throughout the drainage network, whereas Fig. 8 illustrates how often a specific

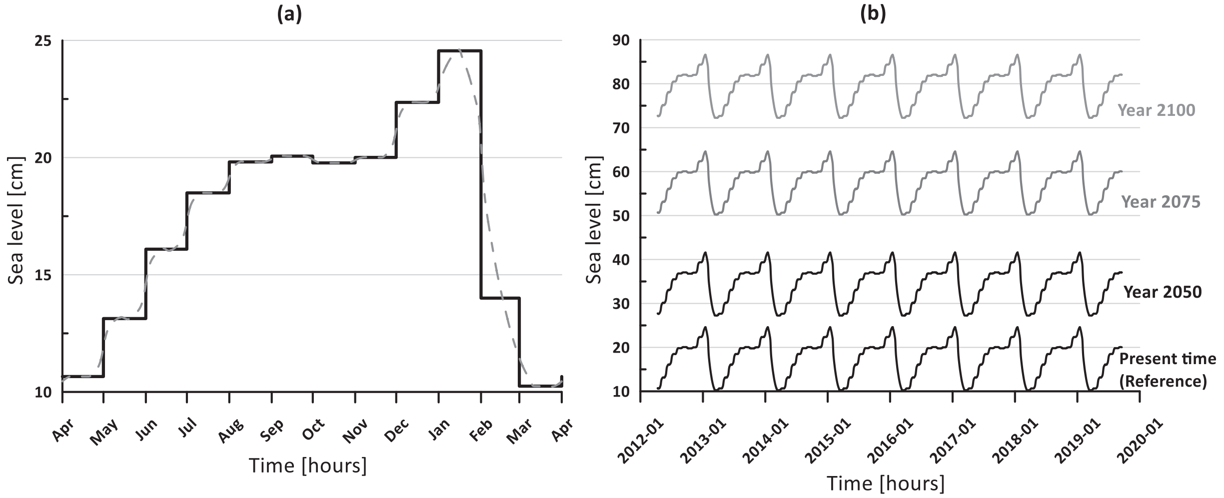

Fig. 5. **a)** The average monthly sea level variation according to a Fourier analysis using hourly time steps. The smoothed Fourier curve is also presented. **b)** The average yearly sea level representing today's situation and the year 2050, 2075 and 2100. The reference system in both figures is RH2000 and the time step resolution is one hour.

Table 3

Developed scenarios for simulation using rainfall data according to Fig. 2, storm surges according to Fig. 4, and average sea level according to Fig. 5.

Timeframe	Current state (Reference)			2050			2075			2100		
Scenarios	Rain	Average sea level	Storm	Rain	Average sea level	Storm	Rain	Average sea level	Storm	Rain	Average sea level	Storm
Scenario 1	*	*										
Scenario 2				*	*							
Scenario 3							*	*				
Scenario 4										*	*	
Scenario 5	*		*									
Scenario 6				*		*						
Scenario 7							*		*			
Scenario 8										*		*
Scenario 9	*											
Scenario 10				*								
Scenario 11							*					
Scenario 12										*		

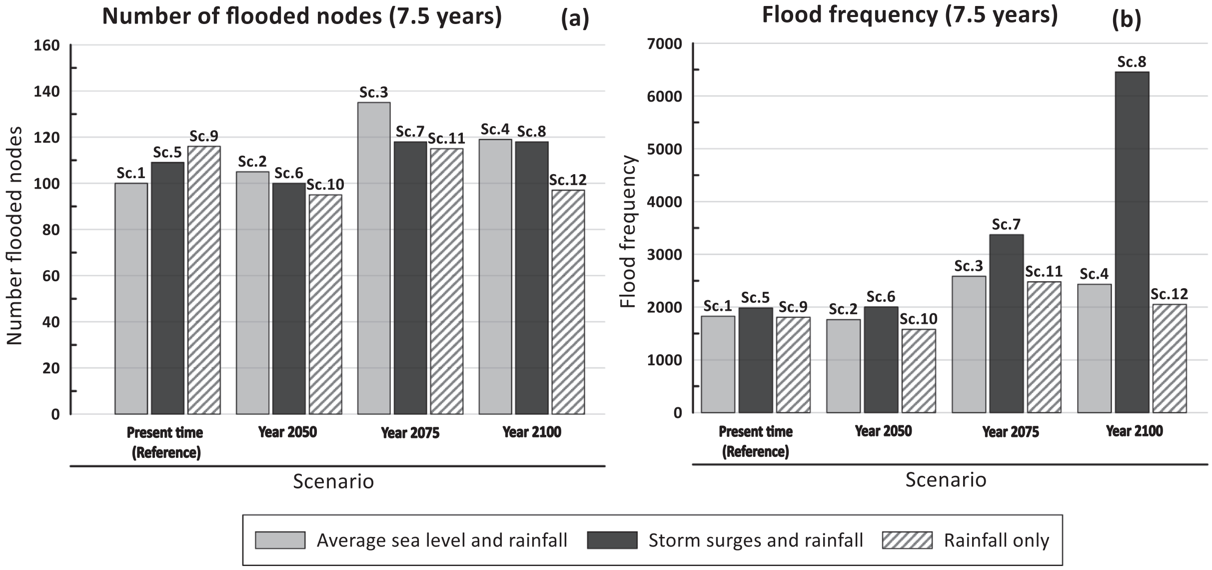

Fig. 6. **a)** Number of flooded nodes (NFN) and **b)** flood frequency (FF) for a 7.5-year long period for different scenarios. Sc. = Scenario.

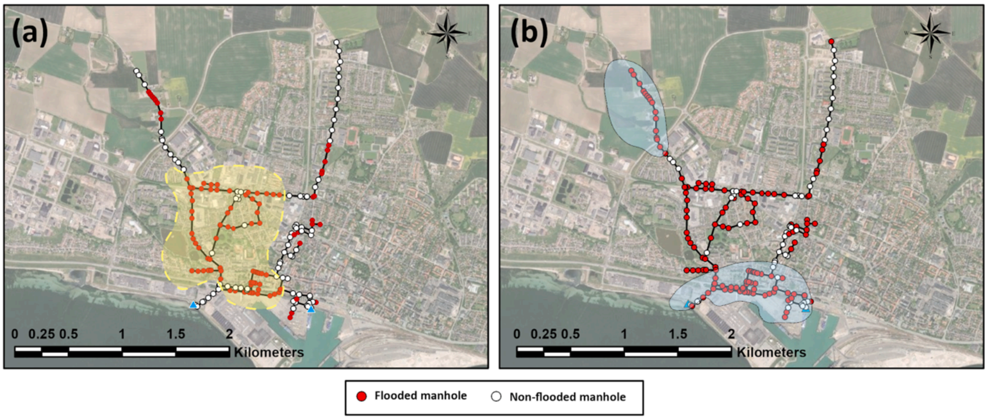

Fig. 7. The spatial distribution of flooded nodes **a)** in today's case: Scenario 1, NFN = 100. The marked area in yellow shows where flooding is more prone to occur; and **b)** in the year 2075. Scenario 3, NFN = 136. The encircled areas show vulnerable hotspots. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

manhole is prone to be flooded (by varying the size of the marker). The scenario that induces a "worst-case" (Scenario 3 in Fig. 7b and Scenario 8 in Fig. 8b) is presented together with corresponding compound events for today's case (Scenario 1 in Fig. 7a and Scenario 5 in Fig. 8a) to determine the relative difference. Note that "today's case" including Scenarios 1, 5 and 9 are reference scenarios and must be interpreted

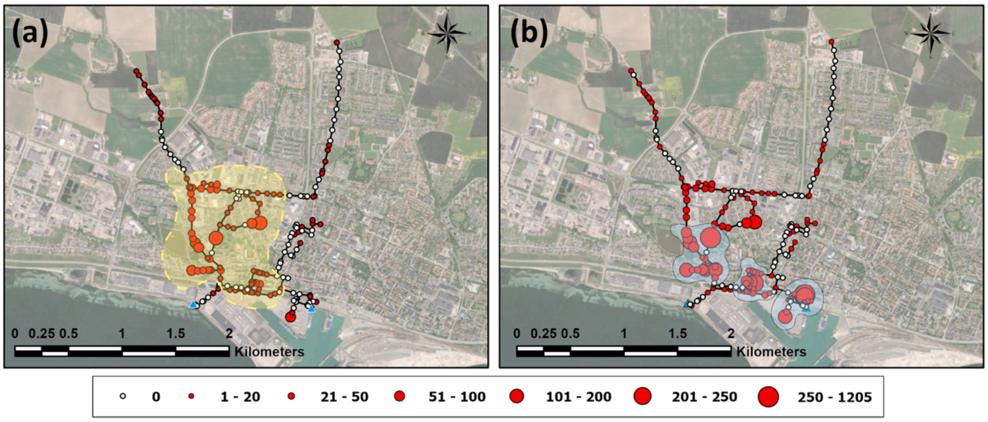

Fig. 8. The spatial distribution of flood frequency **a)** in today's case: Scenario 5, FF = 1984. The marked area in yellow shows where flooding is more prone to occur; and **b)** in the year 2100. Scenario 8, FF = 6455. The encircled areas show vulnerable hotspots. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

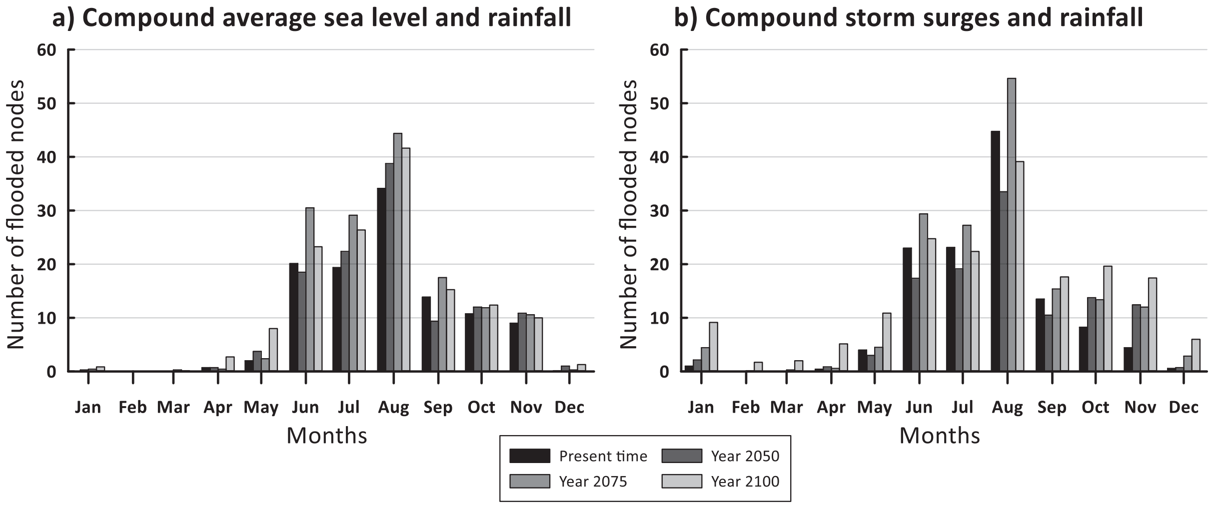

Fig. 9. The temporal distribution of NFN for **a)** the average sea level and rain; and **b)** for storm surges and rain in today's case and in the year 2050, 2075 and 2100. Sc. = Scenario.

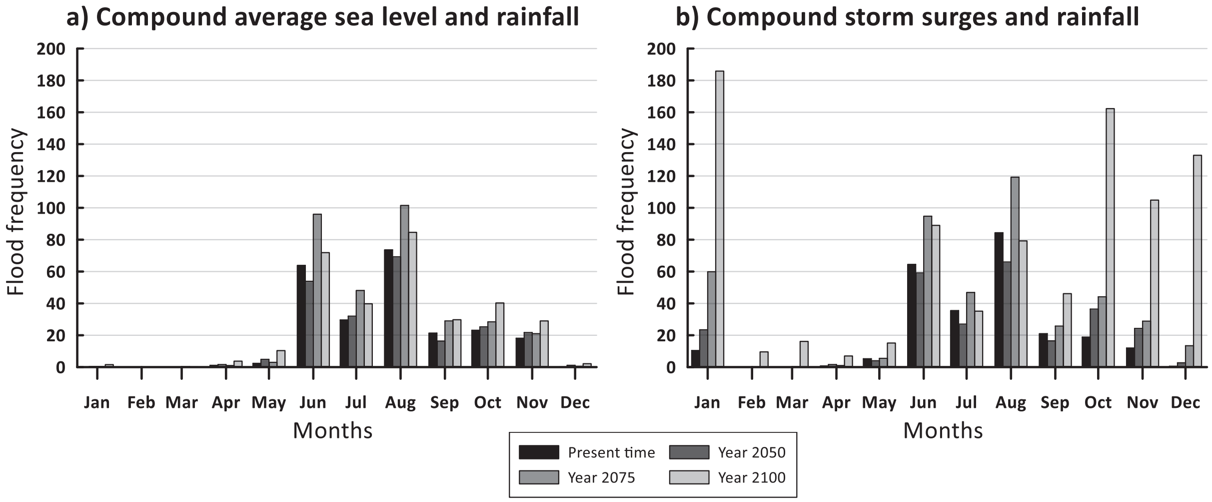

Fig. 10. The temporal distribution of FF **a)** for the average sea level and rain; and **b)** for storm surges and rain in today's case and in the year 2050, 2075 and 2100. Sc. = Scenario.

according to the context of this study and shall not be considered as actual measured or expected performance since the developed model was not calibrated. See Section 2.3 for further explanations.

In today's case, the flooding is pronounced in the central part of the system. A "worst-case" is found for the climate scenario 2075 when rain and average sea level were modelled (*Scenario 3*), at which the NFN increases with 36% relative to today (*Scenario 1*). Much of the increase is assigned to the manholes located close to the sea and those belonging to the western main pipeline (see Fig. 7).

The highest FF is observed in *Scenario 8*. The combination of storm surges and rain in the year 2100 leads to a 225% rise in FF compared to *Scenario 5* (see Fig. 8). The most severe increase in FF is seen in the nodes located downstream of the pipe network. Three hotspots are identified and marked in Fig. 8b.

Temporal variation (NFN and FF)

Monthly averages of NFN and FF are computed to describe how the drainage failure relates to an annual pattern. The monthly mean of NFN reaches its maximum value at 190 nodes, which corresponds to the number of manholes in the drainage system. As for FF, no upper limit is defined.

The temporal distribution for NFN and FF are shown in Figs. 9 and 10, respectively. The results collectively infer that flooding occurring in today's settings (Scenario 1 and 5) follows a somewhat bell-shaped curve, where the most severe situation is found in summer with a peak in August.

Two different behaviors are observed when focusing on NFN in Fig. 9. The results suggest that a rise in an average sea level amplifies the inundation during summer, yet the temporal distribution of flooding remains relatively unchanged. However, when storm surges are allowed to impact the drainage system, the annual pattern is altered with future scenarios leading to floods all year around (Fig. 9b). The joint effect on the drainage system in terms of FF due to rainfall and SLR is noticeable independent of the modelled sea boundary. With a rise in average sea level an increase in flooding is observed. in summer as well as in autumn (Fig. 10a). As in the case for NFN the temporal distribution does not change to a high degree, though the flooding situation becomes more severe in the year 2075 and the year 2100 (Scenario 3 and 4).

Fig. 10b depicts a distinguishable change in seasonal behavior going in which summer is no more the only season for pluvial flooding in future projections. The observed change shows that in future climate scenarios, pluvial flooding is expected to occur during autumn/winter as well. This trend is emphasized for the combined rainfall and storm surge simulation in year 2100 (scenario 8). This scenario has by far the heaviest impact on the urban drainage system in terms of FF.

Stressors

Monthly averages are used to estimate the drivers stressing the system to flood (*Scenario 1–8*). The results are sorted into time periods using normalized flood frequency, i.e., FF:NFN, to be able to compare different scenarios. Normalized flood frequency (Fig. 11) perspicuously reflects the relative importance of rain, average sea level, and storm surges stressing the urban drainage system to fail both today and under future projections.

As seen in the case of present time in Fig. 11, the FF:NFN is approximately constant for all months between the present state until 2075 implying that the drainage failure in today's case is primarily derived from rainfall. Note that until 2075, the FF:NFN-ratio for *rainfall only* scenario aligns with that of compound events. January is the only major deviating month (along with December in 2050 and 2075) during this period showing a short-term impact of winter storms on the drainage network performance. In contrast to the period up to 2075, in 2100 the normalized flood frequency for the compound effect of rain and storm surges (*Scenario 8)* significantly diverges during autumn and winter for a period of about 6 months displaying elevated flood frequency.

Evaluating the flood drivers for the year 2100 reveals a distinct differentiation between the possible stressors. The flooding in autumn and in winter is significantly driven by the compound effect from the storm surges and rain events. In addition, it is worth noticing that the inundation is still mainly rain-induced during the summer period. It is also seen that spring-related manhole surges are occurring during February and March in 2100 which were found to be flood-free months in all the preceding years.

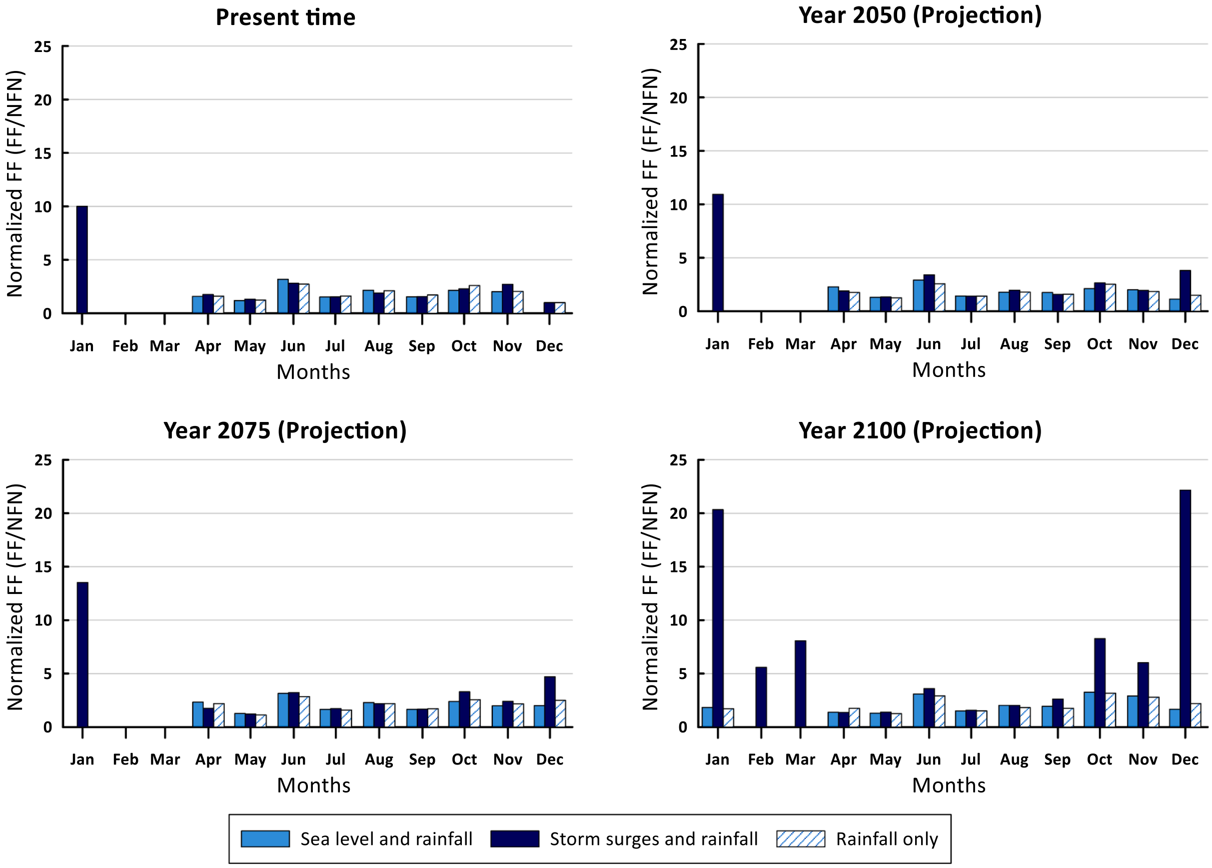

Fig. 11. The relative importance of rain, average sea level, and storm surges stressing the urban drainage system to fail both today and under future projections, expressed as normalized flood frequency.

Discussion

The spatial distribution of flooding in today's situation reveals a hotspot in the central part of the system, underpinning the need for paying extra attention to this area. The reason for this issue is probably originating from a combination of factors which are highlighted when analyzing the profile of the pipe system. These include parameters such as multiple water divides in the pipe system, loops leading to accumulation of water, and heterogeneous invert levels relative to the ground levels. Moreover, the existing pipe system does not have a uniform shape which generates local bottleneck effects and eventually floods. The spatial distribution of flooding is important knowledge for local communities and governmental bodies for decision making. The hotspots do not only map the weak spots in terms of resilience, but they do also shed light on the areas that require improvement to promote equity of water services in society.

Understanding the performance in today's climate is essential to develop and retrofit the pipe system since it is already failing on multiple occasions. In this regard, the current study contributes by providing a benchmark enabling comparative analysis. For instance, other studies examining the impact of changing land use or implementation of blue-green infrastructure on an urban drainage system can utilize the results describing today's case.

The results of today's case are in essence a validation of historical weather patterns, namely cloudbursts overwhelming the drainage system during summer whilst rain together with storm surges impact the system far less in autumn. However, storm surges (incorporating sea level rise) will become the dominant stressor in the future through the exacerbation of FF. Average sea level per se is also pushing the NFN in future scenarios, although its impact is not as considerable as the impact of storm surges is on FF. This is seen in *Scenario 3* and *Scenario 8* in terms of NFN and FF, respectively.

The average sea level is seemingly a more influential factor compared to storm surges in terms of NFN. One plausible explanation might be the dynamic behavior of the sea. Storm surges cause large oscillations which allow the pipe system to drain off backwater. In contrast, as the average sea level is kept at a stable level it is more likely to amplify the effect from any rainfall. Thus, the system becomes more sensitive towards light rainfalls.

The rise in average sea level slightly intensifies the NFN and FF without necessarily altering the temporal pattern from one season to another. Storm surges, on the other hand, drastically change the annual cycle which in the future will result in floods all year-round giving rise to both indicators. A tipping point is presumably found between 2075 and 2100. In this period, storm surges are the main driver pushing up the FF value in winter and in spring. It should thus be noted that the flood water pushed out of the pipe system in 2100 will probably be of brackish nature, which underlines the adoption of prospective measures regarding drainage maintenance, flood management, public health, etc. In addition, the timing of the observed tipping point in urban drainage failure corresponds to IPCC's reported tipping point of the recurrence rate of storm surges in the Baltic Sea [43].

In terms of spatial distribution, the nodes closer to the sea will heavily be affected as a response to sea-level rise. When the system is exposed to an increase in the average sea level, the western pipe system was proven to be more sensitive. Linking the spatial distribution to storm surges, three hotspots can be identified within the downstream area.

The results of this study confirm the findings of Olsson et al. [17] demonstrating that rain is the main contributor to urban flooding in today's climate. However, previous studies did not consider 1) the change in temporal variation, i.e., accounting for winter-related pluvial floods in the future due to constrained discharge capacity of stormwater pipe network by increased sea level, 2) the emerging significance of sea-level rise in future climate, and 3) the cooccurrence of rain- and sea events in the future [44–46]. Neglecting these considerations lead to an uncomplete and limited understanding of future urban flooding and its consequences.

This study underpinned the importance of considering cooccurrence, temporal variation, and stressors altogether to have a more holistic and comprehensive picture of possible flooding scenarios in coastal cities. This knowledge does not only flag and support the need of climate change adaptation measures, but it also calls for innovation. Adaptation measures including blue-green infrastructure have so far been implemented in southern Sweden based on the assumption that heavy rainfalls primarily occur during summer and early autumn. However, this study shows that such an assumption might not be valid in the future climate. It is therefore relevant to rethink adaptation strategies. Since flooding can be derived from both upstream and downstream boundary conditions, it is important to define the main stressor. It is also crucial to map the temporal distribution of these events to ensure effective adaptation. For example, infrastructure relying on evapotranspiration may not be the optimal choice if winter rain triggers flooding. Likewise, installing retention/detention basins upstream the pipe system—as recommended by Haghighatafshar et al. [9] and Kaykhosravi et al. [47]—might not relieve the pressure if sea level overwhelms the system. This is also in line with multi-hazard risk assessment methodology which underlines the need for planning of infrastructure as well as mitigation and adaptation measures through a comprehensive and holistic approach by developing a multi-hazard risk map and understanding different interrelations between hazards and their corresponding measures [48–50].

Another aspect arising with the findings of this study relates to social equity. The fact that sea-level rise creates more flooding is no surprise, but the drivers causing the flood can be vague and challenging to identify. The rise in the average sea level generates more distributed floods while storm surges produce more condense and frequent floods. In other words, either more people will get affected less frequently or fewer people but more often.

Trelleborg cannot exclusively depend on gravity to drain the city in the future due to sea-level rise. The municipality would therefore benefit from considering adaptation measures and retrofitting. The implication of the current study provides answers to where and when the flooding might probably occur. It also informs about the magnitude of flooding and the underlying drivers and stressors. This is fundamental knowledge for decision making when aiming for preserving local communities as well as establishing new development areas. The current stormwater drainage system demonstrates little resiliency and adaptability against climate change which might endanger social security.

This study integrates two climate indices (rainfall and sea-level variations) demonstrating the importance of combining the two. However, more detailed modelling of the stressors might be required for the purpose of designing adaptation solutions. This includes methods that have both the capacity and the flexibility to incorporate various changing factors for different intensity levels, for example, Quantile mapping of rainfall intensities [34] or intensity-dependent scaling/bias correction [51] can be applied. Smaller time frames might also be needed when modelling for such purposes. However, high computational cost and memory constraint have been recognized as the main challenges in this regard. It should also be noted that the probability of RCP8.5 to become a reality is debatable [52]. Hence, there is a need to analyze the urban drainage system performance under other emission scenarios to yield a better understating of the system's sensitivity. Moreover, further cases need to be studied to assess the generalizability of the findings of this study.

Although a change in quantity and frequency of flooding has an implication on water quality, this aspect was not addressed in this study. Moreover, seawater accumulating inside the drainage system might lead to increased sedimentation and pipe corrosion which in turn have an impact on the urban drainage performance. Also, this study did not consider the interchange in terms of infiltration and exfiltration in the pipe system.

Conclusions

This study developed a methodology to account for long-term rainfall and sea-level dynamics to comprehensively assess the performance of a coastal urban drainage system, in which *number of flooded nodes* and *flood frequency* were used as indicators. This study underlines the value of fast modeling techniques as the preparation and analysis of long-term data is computationally demanding.

Through the application of the developed methodology in the city of Trelleborg in Sweden, it is shown that the stormwater system frequently fails throughout the pipe system in today's climate. Nevertheless, future scenarios are causing more floods in comparison to the present state. Although the impact of sea level rise is not evident today, a tipping point is likely to occur between 2075 and 2100, after which storm surges become a major driver for drainage failure. This leads to high flood frequencies, especially in areas located downstream the system.

Based on the hydroclimatic data collected in Trelleborg, future will presumably unfold more and frequent flooding in winter as well due to the growing impact of sea level rise and storm surges in combination with rainfalls. This has a great implication on choosing adaptation measures. It is not only essential to consider the geographical pattern of flooding, but the nature and timing of the floods are also critical for sustainable decision-making. Overall, the projected drainage performance in this study calls for a comprehensive adaptation strategy in Trelleborg, aligned with multi-hazard approach, to cope with sea level- and precipitation-related changes the future might unfold.

CRediT authorship contribution statement

Isabelle Laster Grip: Conceptualization, Investigation, Methodology, Project administration. **Salar Haghighatafshar:** Methodology, Project administration, Visualization. **Henrik Aspegren:** Supervision, Resources, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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