Combined effects of high water level and precipitation on flooding of Gothenburg, Sweden

Sörensen, Johanna; Bengtsson, Lars

2014

Combined effects of high water level and precipitation on flooding of Gothenburg, Sweden

Johanna SÖRENSEN[1]* and Lars BENGTSSON[1]

[1]*Water Resources Engineering, Lund University, Lund, Sweden*
**Corresponding author's e-mail: johanna.sorensen@tvrl.lth.se*

ABSTRACT
In the future, both rising sea water level and higher precipitation are expected due to climate change. Gothenburg is one of the cities in Sweden most affected by flooding in urban areas. Flooding is caused by very high sea level, but also as a consequence of heavy rainfall over the city. It is unknown whether high sea level or heavy rainfall is the most important reason for flooding, or if the combination of them causes the most severe flooding. Flooding caused by combinations of extreme water levels and rains in Gothenburg, are simulated using Mike21 for two scenarios: present climate and year 2100. A digital elevation model is used as input together with water level data from the harbour (Torshamnen) and CDS-rainfall (Chicago Design Storm). In present climate, extreme rainfall and extreme sea water level give more or less the same amount of flooding. If a greater part of Gothenburg is taken into account, extreme precipitation is expected to be the most important factor. In year 2100, the area along the harbour is flooded more severely by a 100-year water level, as the level of the quay is exceeded. In future climate, flooding from sea surge will cause more severe flooding.

KEYWORDS
Extreme precipitation; Sea water level; Flooding; Gothenburg; Modelling

INTRODUCTION
In Europe, like in the rest of the world, recent floods have hit one city after another. Urban flooding lead to big costs, especially in central areas of the city. In Copenhagen, Denmark, a big flood hit the whole city in 2011. Between 90 and 135 mm rain poured down in the central areas during two hours (Woetmann, 2011). In total, the rainfall continued for over four hours and 177 mm was measured in the most central Copenhagen. Copenhagen is situated only 240 km south of Gothenburg, Sweden, the study area for this work. The insurance cost for the Copenhagen cloudburst was estimated to more than 800 million USD (Swiss Re, 2011). A few years before, in 2002, another flooding occurred on the island Orust, outside Gothenburg. The island was hit by 200 mm of water during one night and 40-90 mm the following night. Several villages were isolated and the damages covered by insurance companies were estimated to 123 million SEK (~20 million USD) (MSB (Swedish Civil Contingencies Agency), 2013). If a similar storm would have hit Gothenburg, the monetary losses have most likely been much higher, like in Copenhagen.

A cloudburst like Copenhagen 2011 or Orust 2002 has not hit a dense urban area in Sweden in recent history. However, an assessment of flooding in Sweden, suggests Gothenburg being one of the 7 cities most threatened by flooding (MSB (Swedish Civil Contingencies Agency), 2011). A recent flooding in Gothenburg, in December 2006, shows that the city is threaten by the combination of high water levels in the sea and heavy rainfall. Rainfall exceeding 300 mm during 2 weeks resulted in high river flow. The return period of the storm was estimated to 10–50 years, and high sea water level aggravated the situation. Many buildings were flooded, and traffic on both rails and roads was stopped. In December 2011, Gothenburg was again flooded due to high flow in combination with high water level in the sea. The water level was 146 cm above mean sea level, and 52 mm of rain fell in 48 hours.

Flooding from sea and flooding from extreme storm water events have been explored in many studies (e.g. Bowering *et al.*, 2013; Hallegatte *et al.*, 2010; Morita, 2011; Zhang *et al.*, 2013), but few works have been conducted on the combined effects of them. It is therefore unknown whether high sea level or heavy rainfall is the most important risk for flooding, or how severe flooding the combination of them gives. The scope of this paper is to investigate the causes and consequences of the most severe flooding in Gothenburg, and to determine the probability of combined events with extreme flooding and extreme precipitation.

Study area

The central area of Gothenburg was developed in 1621 and canals where constructed to drain the low-lying, clayey area. The study area is surrounded by canals, see Figure 1, and is a 93 ha area in the oldest part of Gothenburg (Lindgren, 1815). Today the study area is developed with a combined system. In total the sewer system covers an area of 16.300 ha of Gothenburg, where only 20% is combined system (Gothenburg City *et al.*, 2007), while the rest is separate storm water and sewer system. Gothenburg has no bigger green areas in the city centre or close to the riverside, which makes the city static and not resilient. Most of the green areas are in the hills, where they are least needed when it comes to flood resilience.

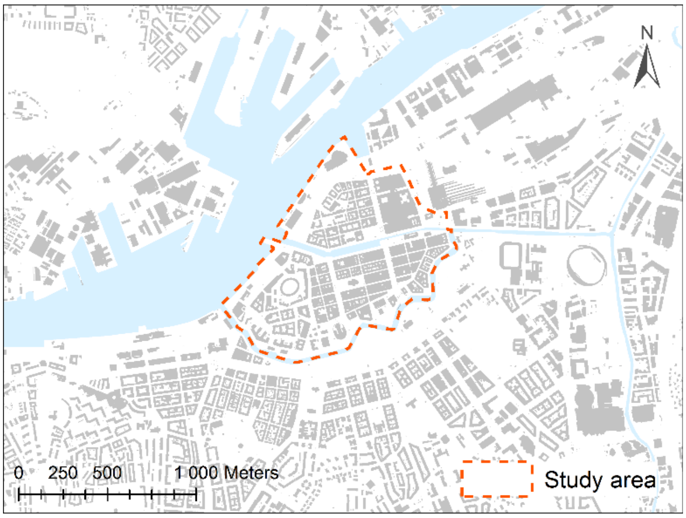

Figure 1. Study area in Gothenburg, Sweden. The area is 93 ha and situated by Göta River.

The climate in Gothenburg gives a more or less evenly spread rainfall during the year, with monthly precipitation of 40–83 mm (SCB, 2013). The hourly intensity of rainfall for return period of 1, 5 and 10 years are 32.2, 56.9 and 69.8 mm/hr, respectively (Hernebring, 2006). In future climate, Gothenburg city can expect more intense rainfall, especially in the autumn. Today the most intense storms are seen in late summer. The sea water level, both the mean and extremes, will rise in the future.

METHODS

Flooding, caused by combinations of extreme water level and precipitation in Gothenburg, now and in the future, is determined using Mike21 from DHI. Variable water level in the harbour is combined with different rainfall scenarios in the simulation. 2-dimensional flow on land is simulated and flooded areas analysed. As input to the model, DEM (digital elevation model), rainfall, water level at boundaries, resistance (Manning's M), and eddy viscosity are specified. Mike21 was chosen because of the possibility to describe both overland flow from rainfall, and to use variable water level in the sea as a boundary value in the model.

Digital terrain elevation data is collected from the Swedish national elevation model (NHH) which has a resolution of 2x2 meters. The uncertainty of the elevation model is vertically 0.1 m and horizontally 0.3 m in flat terrain (MSB (Swedish Civil Contingencies Agency), 2012). The model is modified to take buildings into account. As suggested by DHI (2012), all buildings have been lifted 4 meters over the DEM, as they are excluded in the DEM data, while the streets have not been corrected for, due to lack of data. By blocking out the buildings, possible storage volume inside buildings are eliminated in the model (Syme, 2008). The missing storage volume inside buildings is expected to be of minor importance in this case.

The study area is mostly impervious, homogenous pavement with almost no green spots and therefore the Manning M is set to 40 $m^{1/3}/s$ for the whole area. It is assumed that all precipitation will contribute to runoff, and that no infiltration or evaporation takes place during a storm. As mentioned before, flow in the sewer system is neglected in the simulations, as if the system is not functioning during the storm, due to lack of data. The area is surrounded by canals, and therefore, not directly affected by flow from upstream areas. The flow in the (combined) sewer system is neglected since in extreme situations, the system is drowned and the very large flows outside the conduit systems are the dominating ones.

In Mike21, a depression storage of 1.65 mm is used, which means that runoff at a specific spot does not occur until this depth is reached.

Scenarios

In total, eight flooding scenarios are simulated: four with present climate and four in the expected climate for year 2100. Two sea water levels (mean and 100-year maximum) are combined with two precipitation scenarios (1 and 100 year event). W means sea water level and P means precipitation. For the present climate scenarios, sea water levels are taken from statistics for the period 1887–2010 (SMHI, 2011) and precipitation rates from the period 1973–2004 (Hernebring, 2006). Similar events for year 2100 are found in the climate change assessment of Western Sweden from SMHI (SMHI, 2011).

Water level data used is a modified time series from Torshamnen, a measuring station situated 10 km southwest of the study area, which is set as a 920 metres long boundary around the harbour (northwestern corner of study area). An initial water level, corresponding to the initial water level of the boundary, is set for the rest of the harbour. The extreme situations have a maximum water level of 1.65 m (W100, T = 100 years for 1966–2010) for the present climate, and 2.36 m for year 2100 (SMHI, 2011). An event from 1st June 1985 was chosen, and required centimetres, to reach 1.65 and 2.36 m maximum levels respectively, were added over the whole series.

Precipitation is constructed as a CDS-rainfall (Chicago Design Storm), according to the Danish organisation Spildevandskommitéen (SVK, 2006). Is has a duration of 20 hours and a central peak. It is tested to be very similar to the Swedish standard CDS-rain from Dahlström (2010). The 1-year event (P1) gives in total 30.5 mm of rain for present climate and 38.1 mm for year 2100, and the 100-year event (P100) gives in total 90.4 mm of rain for present climate and 113.1 mm for year 2100. The year 2100 events are expected to be 25% bigger than in the present climate.

RESULTS AND DISCUSSION

Table 1 shows area simulated to be flooded by more than 10 cm during simulation with high and low sea level in combinations with high and low precipitation. Around 13-15 ha (15–17%) are flooded with at least 10 cm of water in the 'present'-scenarios and around 13-19 ha (15–22%) in the scenarios for year 2100. The 'present'-scenario with low water level and little precipitation (W0/P1) is used as a base scenario with index 1.00. Corresponding scenario for year 2100 has only slightly more flooded areas, index 1.01. For the 'present'-scenarios, extreme precipitation have a slightly higher effect (1.08) on flooding than extreme sea level has (1.05). For the year 2100 scenarios, extreme sea level is more important (1.38 compared to 1.11 for precipitation).

Table 1. Areas flooded >10 cm (present climate and year 2100) in simulations with high and low sea level (W) in combinations with high and low precipitation (P). Percentage of total area flooded is shown in parentheses together with index of flooding.

Areas flooded >10cm,'present'	Low precip., P1	High precip., P100
Low sea level, W0	13.04 ha *base sc.* (15.0%, 1.00)	14.04 ha (16.2%, 1.08)
High sea level, W100	13.70 ha (15.8%, 1.05)	14.70 ha (16.9%, 1.13)

Areas flooded >10cm, y2100	Low precip., P1	High precip., P100
Low sea level, W0	13.12 ha (15.1%, 1.01)	14.53 ha (16.7%, 1.11)
High sea level, W100	17.95 ha (20.7%, 1.38)	19.19 ha (22.1%, 1.47)

Rather obvious, areas close to the water are more affected by a higher sea water level, compared to areas further from the coast. As can be seen in Figure 2, the area along the canal is more flooded in the W100-scenario compared to the W0-scenario (see A). Flooding from rainfall affects areas further from the coast more, and there are more flooded areas in the P100-scenario compared to the P1-scenario (see B). The same pattern is seen both for 'present' and for year 2100, except that the area at the quay are much more flooded in the W100-scenarios for year 2100 than for any other scenario (see Figure 3). In the year 2100 case, most of the big W100-flooding is indeed noticed along the harbour, but also areas along the inner canal are more flooded than in the 'present'-scenario.

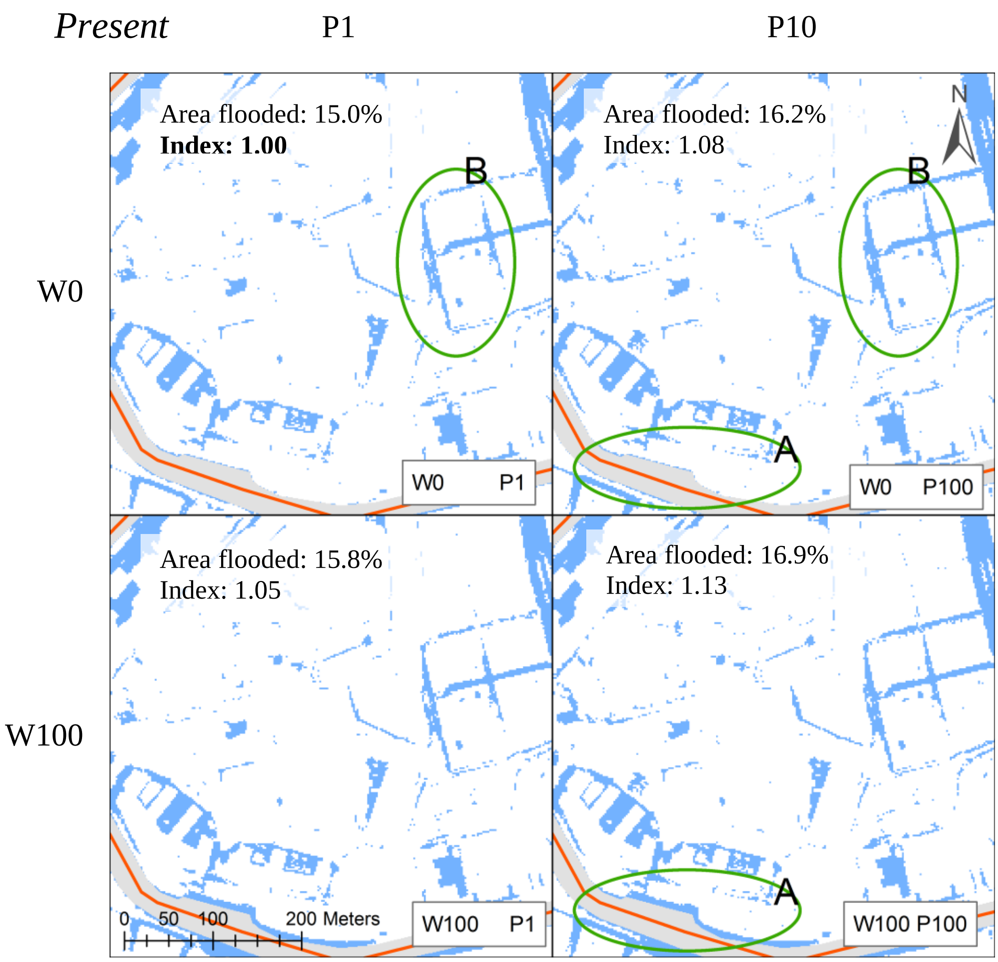

Figure 2. Area flooded (>10 cm) in simulations with high (W100) and low (W0) sea level in combination with high (P100) and low (P1) precipitation. Pixels where maximum inundation during the simulation is >10 cm are shown in blue. The canal (southwest) is shown in grey. The red line shows the border of the study area. This figure shows the southwestern corner of the study area for the four 'present'-scenarios. A and B are described in the text.

It is noted that the difference between the P1- and P100-scenarios are rather small in all simulations. As the sewer system is neglected in the model, this might be the reason for the small difference. With a functioning sewer, one could assume that all precipitation from a 1-year event would be drained from the area, while the system might have problem to entirely drain the area in a 100-year event. Another effect of the missing sewer is seen in the harbour, where a big area is flooded in all eight scenarios (see Figure 3). This area is hidden by a high quay and water from this area is in reality drained. As the combined sewer is not included, this drainage cannot be simulated in the model.

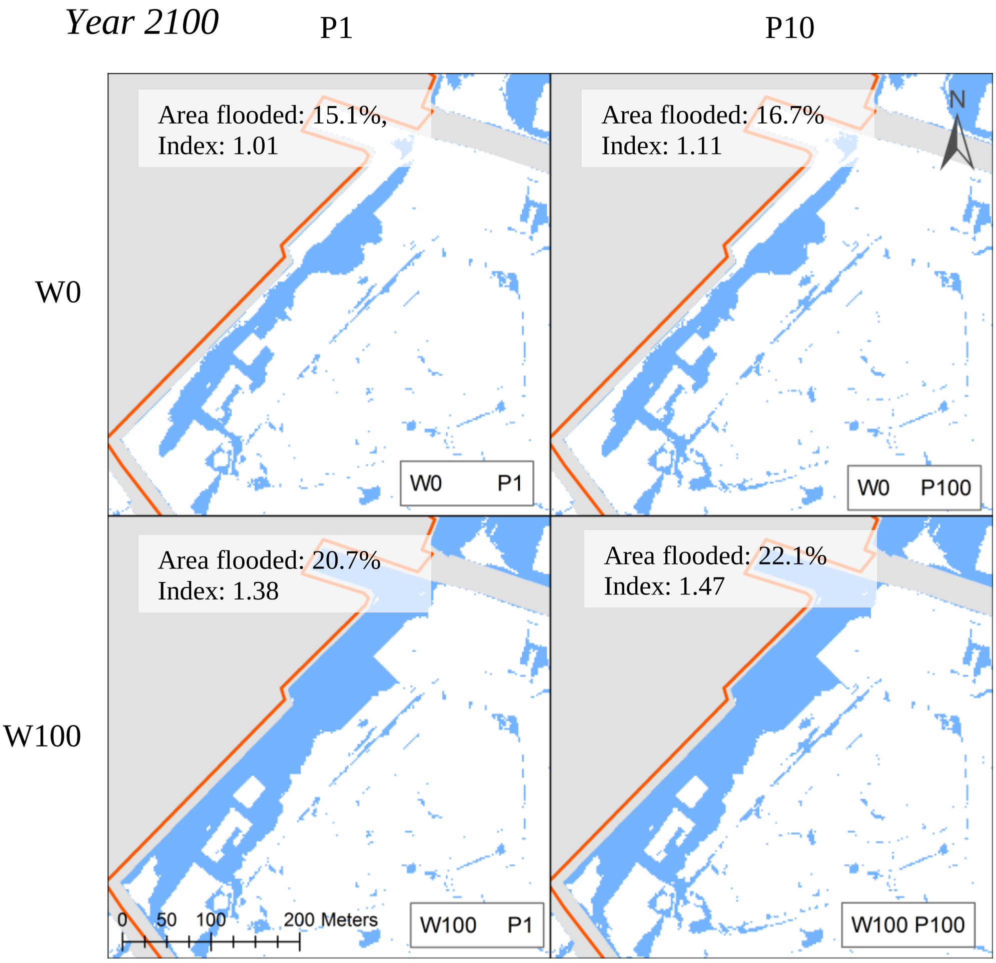

Figure 3. Area flooded (>10 cm) in simulations with high (W100) and low (W0) sea level in combination with high (P100) and low (P1) precipitation. Pixels where maximum inundation during the simulation is >10 cm are shown in blue. The harbour (northwest corner) is shown in grey. The red line shows the border of the study area. This figure shows the northwestern corner of the study area and simulations for the four scenarios in year 2100.

Probabilities

In the climate of western Sweden, large rainfall is seldom related to high sea level. Most of the highest sea levels are seen during autumn storms, while the biggest rainfall events typically occur in late summer.

The relation between daily rainfall and maximum sea level in Gothenburg has been investigated for the period 1968–2011 (44 years). With simple ranking it was found that the 1-year daily precipitation is 33 mm and the daily 1-year maximum sea level is about 100 cm, while the combination of 33 mm of rain and sea level exceeding 100 cm has occurred only once in 44 years. To be able to determine the probability of combinations of large precipitation and high sea levels directly from ranking of the observations, there must be several observed events. With 44 years data, it is reasonable to accept combinations that have occurred at least 7 times, for which the return period is less than 6 years. For less frequent combinations, a theoretical approach is required.

Events more severe than the combination of 30 cm water level and 5 mm precipitation per day has been investigated. It was found that the probability of daily rains, p, exceeding 5 mm was in the range 0.34–0.38 for all sea levels, h, exceeding 30 cm: A mean value of 0.36 is used, meaning $Pr(p>5|h>hx) = 0.36$. It was also found that the distribution daily precipitation exceeding 5 mm was independent of the sea level, meaning $Pr(p>px|(p>5 \cap h>hx)) = Pr(p>px|p>5) = F(p)$, where F is a distribution of precipitation larger than 5 mm. This means that the probability, that large precipitation and high sea levels occur at the same, can be determined as $Pr(p>5 \cap h>hx) = Pr(p>5|h>hx) * F(p) * Pr(h>hx) = 0.36 * F(p) * Pr(h>hx)$, where hx is any water level, h is the actual water level, and p is the actual precipitation.

Table 2. Return period (years) of combinations of large daily precipitation (mm) and high sea level (max cm during the day) in Gothenburg.

p/h	50	60	70	80	90	100	110	120	130	140	150	160	170	180
0						1.1	2.4	5.1	8	12	20	31	49	97
5					1.7	2.2	6.7	14	22	35	55	87	135	300
10				1.5	3.7	4.6	14	30	46	74	117	184	300	
15			1.7	3.3	6.6	14	31	64	99	158	250			
20	1.1	2.1	3.8	8	15	31	67	141	217					
25	2.8	5.1	10	20	37	80	173							
30	5.3	11	20	41	77	164								
35	11	19	35	71	133	300								
40	24	41	76	156	300									
45	41	71	132	300										
50	64	112	209											
55	104	180												
60	169	300												

The probability h>hx is determined directly from observations for h<110 cm. For larger h, h is fitted to a probability distribution. A Gumbel distribution with parameters determined from annual maximum sea levels was used. The final result, showing probabilities as return period in years, are given in Table 2. Return period less than a year or longer than 300 years are not shown in the table. From the statistical approach the W100/P100-scenario, simulated with Mike21, is found to have a return period exceeding 10,000 years. It should be clearly stated that the return period of such an event is very uncertain, as it is based on 44 years of data. It should also be stated that the annual daily maximum rainfall has not changed over the 44 years, while there is a weakly significant increase of the annual maximum sea level.

CONCLUSIONS

Flooding from rainfall is distributed over more or less the whole study area, in both climate scenarios, while flooding from storm surge only takes place close to the harbour and the canals. Also flooding close to the harbour and the canals is mainly caused by storm surge. In year 2100, areas along the water are strongly affected by high sea water level. In the case of a combined event, contribution from high sea water level is only important along the coast.

In present climate, extreme rainfall and extreme sea water level give more or less the same amount of inundation. If a greater part of Gothenburg is taken into account, extreme precipitation is expected to be the most important factor. In year 2100, the area along the harbour is flooded more severely by a 100-year water level, as the level of the quay is exceeded.

The worst scenario (W100/P100) for the present climate is determined to have a very long return period. The correspondent scenario in year 2100 will give bigger flooding, and the probability of combination of high sea water level and large precipitation may increase in the future, since intense precipitation in the autumn is expected to increase in the future in Gothenburg, and high sea levels typically are seen in the autumn.

As future extreme sea water level, future extreme precipitation and the combined probability of them, are very uncertain, it is important to construct cities robust and flexible. The uncertainty makes it impossible for instance to construct dikes in a safe dimension. It is essential for storm surge resilience to move important services further from the coast. It is important to make space for the water from extreme precipitation, for instance by the use of open storm water technology and well-planned landscaping of the terrain around buildings and other constructions.

As mentioned earlier, the sewer is excluded in the model. It is expected that a model with the sewer included would give less flooding, especially for short return periods. In future work, the sewer will be included in the model and coupled to the terrain, if data is made available.

REFERENCES

Bowering, E. A., Peck, A. M., and Simonovic, S. P. (2013). A flood risk assessment to municipal infrastructure due to changing climate part I: methodology. *Urban Water Journal*, 1–11.

Dahlström, B. (2010). Regnintensitet – en molnfysikalisk betraktelse (Rainfall intensities – a cloud physical based study), SVU Rapport. Stockholm, Sweden.

DHI (2012). Urban Climate Change Guidelines – How to achieve sustainable adaptation in urban areas. Hørsholm, Denmark.

Gothenburg City, Gryaab, Urban Water (2007). Systemstudie avlopp: en studie av framtida, hållbara system för hantering av avlopp och bioavfall i Göteborgsregionen (System study of sewer system in Gothenburg Region). Gothenburg, Sweden.

Hallegatte, S., Ranger, N., Mestre, O., Dumas, P., Corfee-Morlot, J., Herweijer, C., and Wood, R. M. (2010). Assessing climate change impacts, sea level rise and storm surge risk in port cities: a case study on Copenhagen. *Climatic Change*, 104(1), 113–137.

Hernebring, C. (2006). 10års-regnets återkomst – förr och nu (Rainfall with 10 years return period – in history and now). VA-forsk. Stockholm, Sweden.

Lindgren, A. (1815). Karta öfver Göteborg och dess förstäder (Map of Gothenburg and its surrounding). Stockholm, Sweden.

Morita, M. (2011). Quantification of increased flood risk due to global climate change for urban river management planning. *Water Science & Technology*, 63(12), 2967.

MSB (Swedish Civil Contingencies Agency) (2011). Identifiering av områden med betydande översvämningsrisk (Assessment of areas with severe flood risk). Karlstad, Sweden.

MSB (Swedish Civil Contingencies Agency) (2012). Ny Nationell Höjdmodell vid havsnivåhöjningar - Analyser av översvämningsrisk och bedömning av erosionskänslighet i strandzonen (New national elevation model). Karlstad, Sweden.

MSB (Swedish Civil Contingencies Agency) (2013). Pluviala översvämningar (Pluvial floodings). Karlstad, Sweden.

SCB (2013). Statistisk årsbok för Sverige 2013 (Statistic yearbook for Sweden 2013).

SMHI (2011). Klimatanalys för Västra Götalands län (Climate analysis for the Västra Götaland Region). Norrköping, Sweden.

Swiss Re (2011). The ripples of heavy cloudbursts. Swiss Re website, Available: http://www.swissre.com/reinsurance/insurers/property_specialty, visited 27 November 2013.

SVK (2006). Regional variation af ekstremregn i Danmark (Regional variations of extreme precipitation in Denmark). Copenhagen, Denmark.

Syme, W.J. (2008). Flooding in Urban Areas-2D Modelling Approaches for Buildings and Fences, in: Engineers Australia, *9th National Conference on Hydraulics in Water Engineering*, Darwin Convention Centre, Australia. pp. 23–26.

Woetmann, N. (2011). Skybruddet over København den 2 juli 2011 (Cloudburst in Copenhagen, 2 July 2011). *Vejret (Dansk Meteorol. Selsk.*) 33, 12–22.

Zhang, K., Li, Y., Liu, H., Xu, H., and Shen, J. (2012). Comparison of three methods for estimating the sea level rise effect on storm surge flooding. *Climatic Change*, 118(2), 487–500.