Assessment of flood hazard in a combined sewer system in Reykjavik city centre

Asta Osk Hlodversdottir, Brynjolfur Bjornsson, Hrund Olof Andradottir, Jonas Eliasson and Philippe Crochet

ABSTRACT

Short-duration precipitation bursts can cause substantial property damage and pose operational risks for wastewater managers. The objective of this study was to assess the present and possible future flood hazard in the combined sewer system in Reykjavik city centre. The catchment is characterised by two hills separated by a plain. A large portion of the pipes in the aging network are smaller than the current minimum diameter of 250 mm. Runoff and sewer flows were modelled using the MIKE URBAN software package incorporating both historical precipitation and synthetic storms derived from annual maximum rainfall data. Results suggest that 3% of public network manholes were vulnerable to flooding during an 11-year long rainfall sequence. A Chicago Design Storm (CDS) incorporating a 10-minute rainfall burst with a 5-year return period predicted twice as many flooded manholes at similar locations. A 20% increase in CDS intensity increased the number of flooded manholes and surface flood volume by 70% and 80%, respectively. The flood volume tripled if rainfall increase were combined with urban re-development, leading to a 20% increase in the runoff coefficient. Results highlight the need for reducing network vulnerabilities, which include decreased pipe diameters and low or drastically varying pipe grades.

Key words | combined sewer, flooding, hazard, modelling, precipitation, rainfall extremes, urban drainage

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INTRODUCTION

Observed and projected increases in air temperature are expected to lead to more intense precipitation because a warmer atmosphere has greater water-holding capacity (Lenderink & van Meijgaard 2010; Trenberth 2011). In the recent past, severe weather has caused major urban flooding events such as the 1997, 2002 and 2005 Central European floods (Ulbrich *et al.* 2003; Kundzewicz *et al.* 2005) and the 2007 United Kingdom floods (Lane 2008). Flooding events have great societal and economic impacts in urban areas (Ashley *et al.* 2005), especially in city centres where a large number of people and important services may be negatively affected.

An assessment of flood risk based on runoff modelling provides a basis for preparing emergency plans and prioritising flood prevention actions and measures. Studies demonstrate that the capacity of existing sewer networks to convey greater runoff volume varies substantially. For example, Denault *et al.* (2006) found that the greater part of the drainage system was adequate to handle a 40–60% increase in rainfall intensity. Berggren *et al.* (2012) predicted 60 and 150% increases in the number of flooded manholes for near (2010–2040) and distant (2071–2100) future climate change scenarios. Ashley *et al.* (2005) estimated that flooding might double as a result of a 20% increase in rainfall. Independent, local flood studies are therefore very important.

Systematic and dynamic adaptation of urban drainage systems is needed to cope with greater surface runoff volume as a result of climate, demographic or land use changes (Arnbjerg-Nielsen *et al.* 2013). Measures need to be flexible, robust and reversible. The monetary value embedded in sewer systems calls for a more effective integrated water management of existing infrastructure (Ashley *et al.* 2007). Sustainable urban drainage systems (SuDS), which store runoff locally via ponds, green roofs and permeable pavements, are viewed as cost efficient, low impact

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solutions. A new geographic information system (GIS)-based decision support tool to select SuDS retrofit solutions suggests that combined sewage overflow spill volume may be reduced by 60–80% during a typical year (Moore *et al.* 2012).

The northernmost capital in Europe, Reykjavik, receives approximately 800 mm of precipitation annually. Total precipitation in Iceland is expected to increase by 1% per decade in the 21st century (Nawri & Bjornsson 2010). Trends in annual maximum 10–60-minute precipitation were found to be insignificant in the past 60 years in Reykjavik (Hlodversdottir 2010). That does not, however, preclude future changes in the statistical characteristics of precipitation, which are influenced by changes in atmospheric circulation patterns (Trenberth 2011; Willems *et al.* 2012). Inter-annual and decadal variations observed in Icelandic precipitation may impede the detection of long-term trends (Crochet 2007).

The present study was initiated on behalf of Orkuveita Reykjavikur, the municipal water utility in Reykjavik. The objectives were to evaluate the flood hazard and the sensitivity of urban drainage systems to a change in precipitation pattern and urban development. Downtown Reykjavik was chosen as the study site because of its important services and plans for increased development which have the potential to increase the loads on an aging sewer network. This work provides a novel comparison of simulated flood hazard using two different types of rainfall inputs: on one hand an 11-year long historical rainfall sequence representing present conditions; on the other hand, synthetic design storms derived from annual rainfall extremes over multiple decades, representing the method for sewer design where precipitation data are scarce. In addition, the diagnosis of structural system components that contribute to simulated and observed flood hazard may help pinpoint weaknesses in other aging networks.

METHODS

Runoff and hydraulic modelling

The MIKE URBAN MOUSE (MOdel of Urban SEwers) package developed by the Danish Hydraulic Institute is a GIS-based urban rainfall–runoff model used for wastewater collection system design in Reykjavik. Sewer flow was simulated in a 1.8×1.2 km (220 ha) downtown area of Reykjavik (Figure 1). The area north of Tjornin Pond is flat and is generally at 4 m above sea level (ASL). Important government, service and cultural institutions are located in this area. Sewage flows under gravity from hills topped with churches (at around 22 and 37 m ASL) (marked as C) down towards the pond or the ocean. A pumping station (marked as P) pumps the wastewater along the coastline eastwards towards a primary treatment facility (beyond the extent of Figure 1).

Pipe data were extracted from the GIS-database owned by the local public utility company Orkuveita Reykjavikur and was imported into MIKE URBAN. In total, 946 pipes (46 km) and 862 manholes with storage capacity of 8,200 m^3 were included in the model. The majority of the pipes were installed before 1950 (Figure 1(a)). Selected pipes have been renewed north of Tjörnin Pond. New additions to the system include separate stormwater

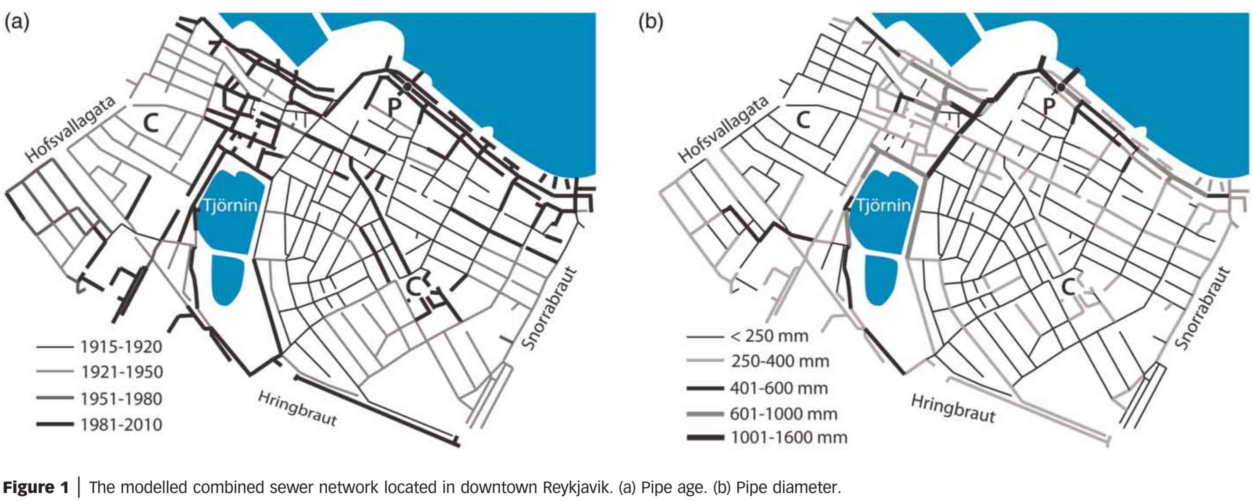

Figure 1 | The modelled combined sewer network located in downtown Reykjavik. (a) Pipe age. (b) Pipe diameter.

collection pipes located along the main highways in the south and the north. Otherwise, almost all of the pipes are combined. A large portion of the pipes are smaller than the current minimum diameter of 250 mm, especially in the residential streets close to the two churches situated on the hilltops. The main sewer collecting wastewater at the convergence of the two hills (dark line, Figure 1(b)) ranges in size from 1,200 to 1,600 mm. Most of the pipes have been lined in the last 20 years to reduce leakage and enhance system performance. No modifications were made to account for possible pipe diameter loss due to lining, and all manhole diameters were assumed to be a standard 1 m diameter. Only flow in the public combined or stormwater pipes was modelled. Domestic wastewater was excluded as it is a negligible flow component during high rainfall. House connections and back-flow check valves used to prevent spillage of sewage into basements are not a part of the public sewer network in Reykjavik and were not considered.

The urban catchment was divided into 845 sub-catchments, characterised as rectangular, divergent or convergent, based on their shape. A separate time area curve was allocated to each shape to characterise the fraction of drainage area contributing to runoff by time. The default initial loss parameter of 0.6 mm was used to account for the wetting and filling of catchment depressions. The composite runoff coefficient (C) of each sub-segment was calculated using GIS layers of houses ($C = 0.9$), roads ($C = 0.9$), sidewalks and parking lots ($C = 0.8$) and pervious green areas ($C = 0.2$). Runoff generated in each catchment is assumed to flow freely down the moderately sized iron grates, i.e. no inlet limitations were adopted.

Model scenarios

Actual rainfall sequence

Digital measurements of rainfall at 10-minute intervals over an 11-year time period (1998–2008) were used as model inputs, hereafter referred to as actual rainfall sequence (ARS). These measurements were taken by the Icelandic Meteorological Office (IMO) on top of a hill at 52 m ASL approximately 2.6 km east of the study area. The maximum 10-minute rainfall intensity was 3.7 mm (22 mm/hour) recorded during a 1-hour storm on 18th June 2003 (Figure 2(a)). A similar 10-minute intensity was also measured during a 10-hour storm on 6th October 2008 (not shown).

In the absence of stream flow data, the model was checked by comparing simulated overflow hours to measured overflow hours at the Ingolfsgata pumping station (unpublished data; Orkuveita Reykjavikur). Modelled overflow hours corresponded within 5% to those measured in 2002 and 2003, suggesting that the simulations are credible and representative of actual flows.

Synthetic design storms

Owing to the lack of long historical records of short-duration rainfall, Icelandic wastewater collection systems are designed based on synthetic rain events derived from rainfall intensity–duration–frequency curves (IDFs) calculated using the M5 method (Eliasson 2000). Incorporating both annual maxima rainfall from the analogue IMO Reykjavik gauge (1951–2000) and new annual maxima from the IMO digital gauge thereafter (Hlodversdottir 2010), the

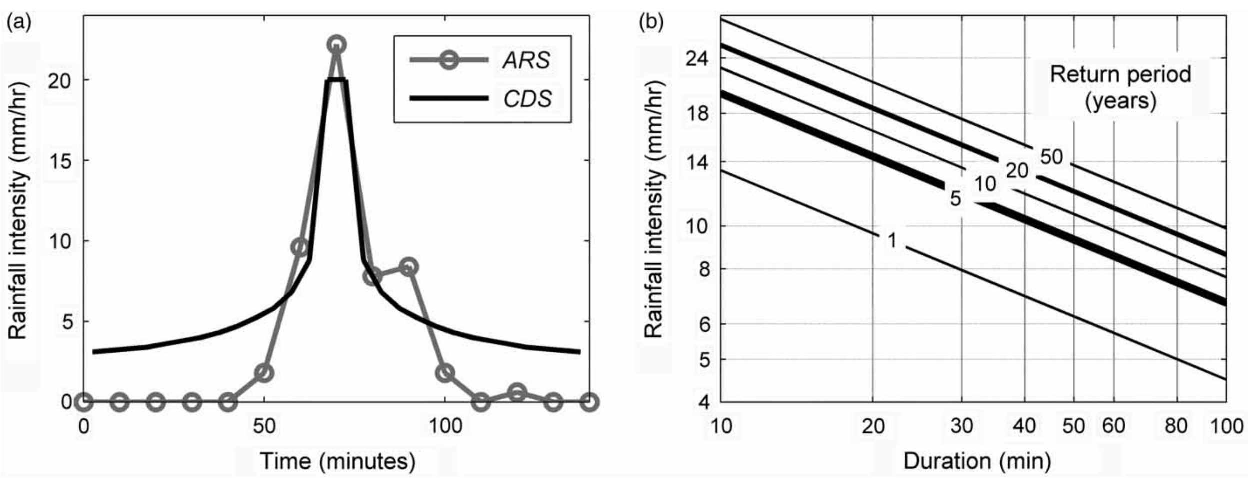

Figure 2 | Rainfall data. (a) Hyetograph for maximum 10-minute rainfall events. (b) IDFs (1951–2008).

peak 10-minute duration rainfall with a return period of 5 years was estimated as 3.3 and 3.8 mm for 10 years, which equates to 20 mm/hr and 23 mm/hr, respectively, see Figure 2(b). Following the local design guidelines (Orkuveita Reykjavikur 2008), symmetrical Chicago Design Storms (CDS; Kiefer & Chu 1957) were derived from these IDFs. The CDS base scenario considers a 140-minute event which incorporates the maximum 10-minute rainfall intensity with a 5-year return period. Figure 2(a) shows that the base CDS slightly underestimates the maximum 10-minute peak rain in the ARS, but overestimates the intensity directly prior to the peak. Design storms associated with longer time-steps (20–30 minutes) and duration (280–420 minutes), or alternatively return periods, were considered.

Change in rainfall and urban development

An initial assessment of trends in short-term annual maximum precipitation in Reykjavik did not give conclusive results (Hlodversdottir 2010). Consequently a 20% increase in rainfall intensity was considered (CDS-R). This is in line with the rainfall scenarios used by Ashley *et al.* (2005). It is a conservative scenario compared to distant future climate change studies which have predicted an increase in extreme rainfall intensity of 20–60% in 2100 (Berggren *et al.* 2012). An urban development across the model area, resulting in a 20% uniform increase of runoff coefficient, was also considered (CDS-D) as well as a combination of 20% incremental rain and 20% urban development (CDS-RD).

Indicators and causes of flooding

Flood hazard was assessed within the 120 ha inner portion of the simulation area, representing 487 pipes and 444 manholes (Figure 3). Flood hazard was evaluated based on four indicators: number of flooded manholes (M); number of full flowing pipes (P), representing system capacity limitations; number of manholes with water level 1 m below ground (M_{-1m}), representing the potential for semi-basement flooding in combined sewer segments; and volume of overflow from manholes (V), representing the magnitude of surface flooding. In the ARS simulation, the sum of M (and M_{-1m}) was calculated over an 11-year time span to obtain an indication of the number of times manholes flooded. Flooding locations were mapped and the causes of overflows were diagnosed by considering the detailed longitudinal sections of selected problematic network segments. Locations of flooded manholes were compared to the locations of reported water-related property damage due to rainfall and snowmelt from 1997 to 2008 (unpublished data, Sjova Insurance Company).

RESULTS AND DISCUSSION

Present flood hazard

During 1998–2011, the ARS predicts 270 m^3 of surface flooding at 12 manholes (Table 1), representing 3% of the manholes assessed. Figure 3(a) shows that overflows (black dots) occur mainly at four locations (labelled 1–4). The number of manholes where the water level may have reached 1 m below ground, potentially leading to semi-basement flooding, is 100, which is substantially greater than the number of flooded manholes. These manholes are mostly located in the commercial–institutional area north of Tjörnin Pond (white circles) as well as streets downhill from the Eastern church (marked as EC). The diameters of the white circles suggest that elevated water levels may have persisted for up to 2 weeks, corresponding to 0.4% of the 11-year simulation period.

Reported water-related property damage due to rainfall or snowmelt (see squares in Figure 3(a)) confirms that flooding occurred at locations 1 and 2. This supports the predictions of the ARS simulation and its ability to identify weak points in the system network. Property damage was reported in three locations that were not flooded in the ARS simulation. As the simulations were conducted in the public network, they cannot predict flooding due to problematic or faulty connections in the private network. Previous research has indicated that flooding incidents in private systems greatly outnumber those experienced in the public sewer system (Ashley *et al.* 2005).

Synthetic event flood hazard

The base CDS simulation predicts twice as many flooded manholes and almost double the flood volume than the 11-year ARS simulation (Table 1). The reason is not due to a lack of high-intensity rainfall, as two rainfall events occurred with maxima comparable to the CDS in the ARS. Rather, the CDS inherently assumes that rainfall maxima of various durations occur during the same design event for a specific return period. The CDS is a conservative design method that overestimates flood hazard.

Figure 3(b) shows that the locations of flooded manholes predicted by the CDS compare well with those

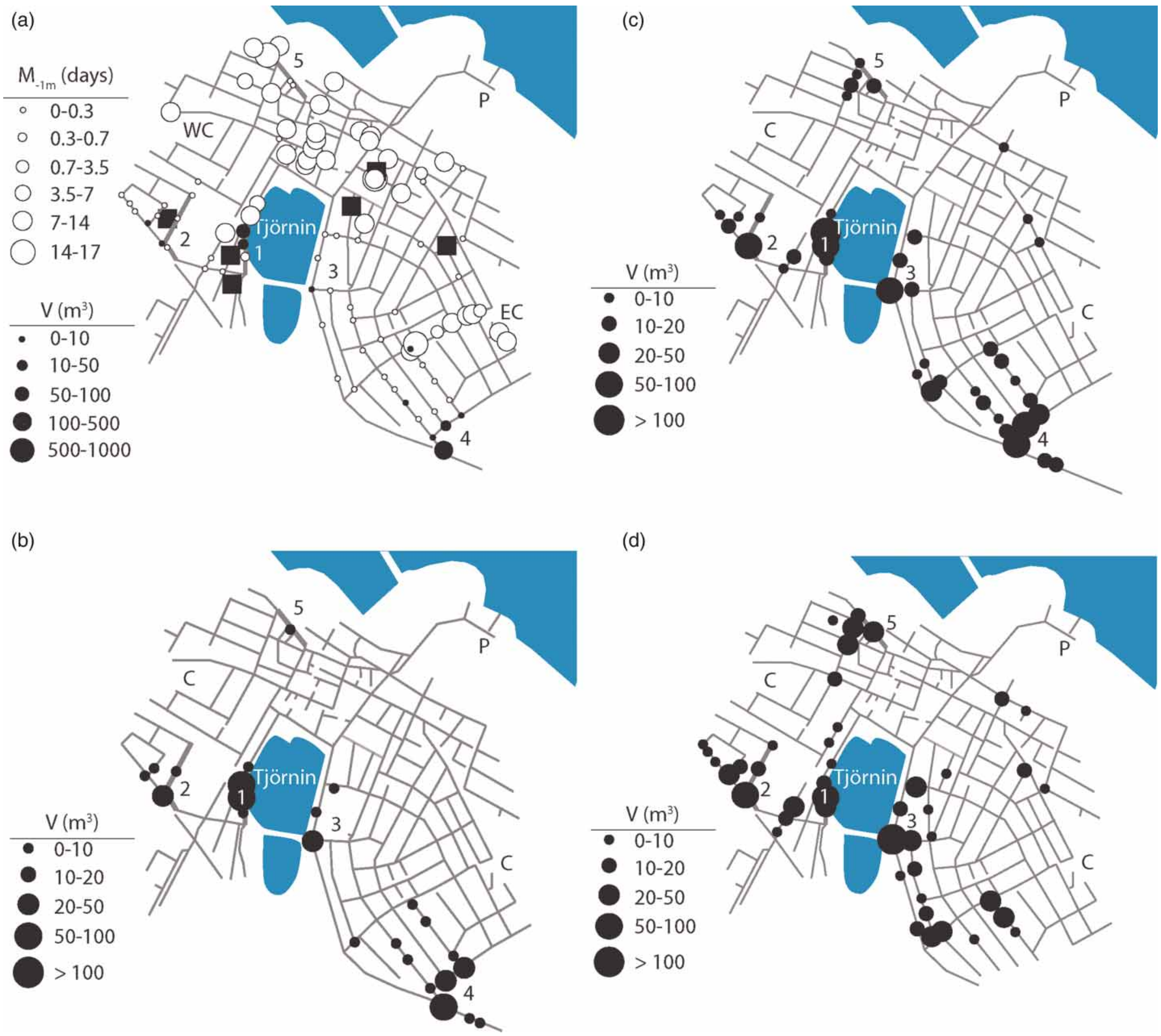

Figure 3 | Locations of flooded manholes in MIKE URBAN scenarios. (a) ARS, (b) CDS, (c) CDS-R and (d) CDS-RD. Water-related property damage locations are indicated as squares.

predicted by ARS (Figure 3(a)). In addition, approximately 30% of the manholes may experience elevated water levels (1 m below ground) as compared to 23% under the ARS (Table 1). This suggests that the current design method based on CDS storms gives representative results for locations of system weaknesses.

Table 1 | MIKE URBAN flooding indicators for downtown Reykjavik

		M		M_{-1m}		P		
Scenario	**Description**	**No.**	**(%)**	**No.**	**(%)**	**No.**	**(%)**	**V (m^3)**
ARS	Actual rain	12	3	100	23	–	–	271
CDS	Synthetic storm	26	6	135	30	136	28	469
CDS-R	20% rainfall increase	43	10	164	37	175	36	852
CDS-D	20% runoff coefficient increase	45	10	164	37	177	36	903
CDS-RD	20% rainfall + 20% runoff increases	62	14	205	46	217	45	1558

Change in rainfall and urban development

Numerical results presented in Table 1 suggest that 20% increase in rainfall intensity (or alternatively runoff coefficient) may almost double the number of flooded manholes, from 6% (CDS) to 10% (CDS-R, CDS-D). Similarly, surface flooding volume is increased by 80–90%. Figure 3(c) shows an emerging weak network segment along Vesturgata Street (labelled 5) as well as increased flooding at the manholes identified in the CDS simulation. The number of manholes with elevated water levels (1 m below surface) and the number of full flowing pipes, however, increased moderately by 20–30%, representing an additional 7–8% of system components. Table 1 suggests that urban development, resulting in a 20% increase in runoff coefficient, on top of a 20% rainfall increase (CDS-RD), roughly triples the base surface flooding to an estimated 1,600 m^3 (Figure 3(d)).

Rainfall extremes of varying duration and return period

Figure 4(a) shows that the number of flooded manholes and the magnitude of flooding volume drop rapidly when increasing the time-step in the CDS from 10 to 30 minutes, corresponding to rainfall peaks of varying duration (Figure 2(b)). The drainage system is most sensitive to intense short rain showers, typical for small networks with short periods of concentration. Figure 4(b) shows that the capacity of the existing drainage network in downtown Reykjavik falls short of current guidelines which require neighbourhoods with important commercial and industrial infrastructure to be designed for maximum 10-minute precipitation with a 20-year return period (Orkuveita Reykjavikur 2008). Such 20-year rainfall would flood 49 manholes and fill 185 pipes, which corresponds closely to the scenario of 20% higher rainfall with 5-year return period (CDS-R, Table 1). Flooding is predicted even for events with a 5-year return period, which is the design acceptance standard used when designing residential areas.

Diagnosis of system weaknesses

Despite a combined system overflow located east of Tjörnin Pond, simulations identify a flood hazard at location 1. Flooding occurred where the pipe diameter decreased from 610 to 500 mm in a segment with only 0.2% grade, which is flatter than the current minimum design requirement of 0.5% grade. The combination of low grades and reduced pipe diameters limits the hydraulic capacity of this sewer segment and increases the hazard of sedimentation and pipe clogging as well as flooding. Simulated flooding at location 5, however, occurred in a segment with a 229 mm pipe, which is under the current 250 mm minimum diameter guideline. A pipe at a steep grade (5%) connects to a same diameter pipe with a far lower grade (1%) and hence a lower water transport capacity. The transition from super-critical to sub-critical flow at this junction also contributes to energy losses, and flooding.

CONCLUSIONS

The likelihood of manhole flooding and pipe surcharge hazard in downtown Reykjavik was assessed based on an

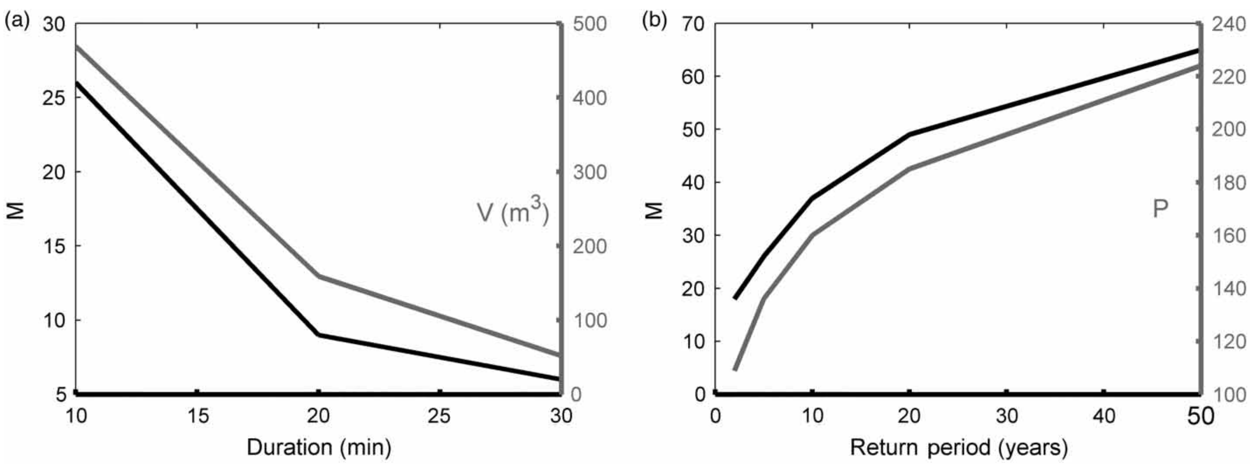

Figure 4 | Flooding indicators for CDS with rainfall peaks of varying (a) duration and (b) return period.

11-year historical rainfall series, as well as synthetic design storms of varying rainfall intensity. Simulations in MIKE URBAN suggest flooding in 3% of network manholes in the past 11 years. The public network does not satisfy current design requirements to convey annual maximum precipitation with a 20-year return period without surcharge. CDS simulations confirm the locations of system weaknesses, while indicating more flooding. A 20% increase in synthetic rainfall (or a 20% increase in the runoff coefficient) almost doubles the number of flooded manholes and flooding volume. Factors contributing to network vulnerabilities are pipes smaller than the 250 mm minimum diameter, low or discontinuous pipe grades and smaller diameter conduits downstream in the piping network. Assuming that precipitation will increase over the coming decades, a timely flood hazard assessment as performed in this study provides a basis for preparing emergency plans and prioritising flood prevention measures and actions including the incorporation of SuDS in any new development or redevelopment.

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