International Journal of Disaster Risk Reduction 67 (2022) 102679

Contents lists available at ScienceDirect

International Journal of Disaster Risk Reduction

journal homepage: www.elsevier.com/locate/ijdrr

Cloudburst-disaster modelling. A new open-source catastrophe model

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A R T I C L E I N F O

Keywords:
Catastrophe model
Cloudburst
Oasis open-source framework
Pluvial flooding
Property-level loss data
Vulnerability curve

A B S T R A C T

Cloudburst flash floods cause big casualties and economic losses. This study primarily investigated if a cloudburst catastrophe (cat) model could be constructed to meaningfully assess such a hazard, exposure and vulnerability in Swedish urban context. Rainfall intensity was used directly as hazard measure, bypassing hydraulic water-level modelling, to predict vulnerability. The Splash (Swedish pluvial modelling analysis and safety handling) cloudburst-disaster model was constructed using the Oasis Loss Modelling Framework, and was based on individual property values and building locations, property-level insurance-loss data, high-resolution geographical data, and rainfall data from a dense municipal gauge network in the city of Jönköping. One major cloudburst event was used to derive a vulnerability curve. The following two events were used for validation and supported the hypothesis that the vulnerability curve changed with time because of municipal flood-risk-reduction measures after the first event. A faulty rain gauge during the first event, replaced by a trustworthy private gauge, clarified the very high sensitivity to cloudburst input. Given the limited amount of loss data, our results were uncertain but they pointed towards possible ways to further this study with other loss data at other locations, possibly using more easily available aggregated loss data. We concluded that a cat model based only on rainfall intensity provided acceptable results, thus providing an opening for future, simplified cloudburst cat models applicable in most geographical contexts where reliable cloudburst data are available, especially in cities with limited topographic data and hydraulic-modelling capacity.

1. Introduction

Flash floods are a chronic problem in many European cities, with projected increase in frequency and magnitude [1,2]. In the light of ongoing urbanisation and climate change there is a strong need for cities to adapt their policies and preparedness to enhance resilience [3]. To prevent and mitigate flood losses in terms of human lives, destruction of buildings and infrastructure, and damages to ecosystems and cultural heritage [4] in the EU member states, this adaptation takes place within the frameworks of the Water Directive since 2000 and the Flood Directive since 2007. Implementation of the Flood Directive in Sweden started with lake and fluvial flooding, complemented in the second 6-year cycle with coastal flooding. Pluvial-flood assessment has so far only been regarded as

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https://doi.org/10.1016/j.ijdrr.2021.102679
Received 10 June 2021; Received in revised form 29 October 2021; Accepted 5 November 2021

Available online 9 November 2021

complementary information for the flood-risk-management planning, if regional and local authorities can provide such material [5]. Pluvial floods are, however, frequent and cause substantial losses in Sweden [6]. For the period 2001–2015, a large majority of the flood-caused insurance claims was caused by cloudbursts [7].

The assessment of pluvial floods is scarcer than that of fluvial floods in most European countries. One reason is the uncertainty about cloudburst location [8], meaning that all vulnerable areas can be exposed, and that large parts of modern cities, as well as infrastructure facilities, need pluvial-flood-risk management. Schanze [8] discuss other challenges of pluvial-flood-risk modelling, such as uncertainties around rainfall amount and forecasts, insufficient capacity of digital-elevation models to vertical resolution of the topographic micro relief, and parametrisation of hydraulic modelling tools. He also concludes that there is limited research specifically on pluvial-flood damages.

Van Ootegem et al. [9] test two approaches to model pluvial-flood damage: a water-depth approach, based on empirical data, and a rainfall-intensity approach. The first uses ex-post flood depth to explain variation in economic damages. The second uses measured rain intensity to explain the same damages. The two approaches explain 9–21% of the damage variance for 346 households in Flanders. The depth-damage approach has a somewhat higher degree of explanation, but the rainfall-intensity approach is less labour- and time-demanding, and could thus be preferable in a warning system where reaction time is limited. The rainfall-intensity approach is also useful in areas with scarce data on hydrologic and hydraulic structures, high-resolution topographic data, or where hydraulic modelling tools are absent. Hydraulic models are site-specific, whereas a damage model based on rain intensity may be less so. Several Swedish flash-flood studies [6,7,10,11] support the hypothesis that cloudburst intensity may be a primary variable to explain insurance claims, thus inviting further studies of the rainfall-intensity approach.

Hazard, exposure and vulnerability must all be addressed to meet the requirements of damage-cost assessment, as well as risk-reduction and adaptation strategies [12–15]. Catastrophe modelling (cat modelling hereafter) is a methodology to do this. Cat models have been developed since the late 1980s [16] to estimate reinsurance needs. A main focus of these models is large disaster events that lead to huge claims from policyholders, where it is crucial that each company has the appropriate level of reinsurance [17]. These models combine the science of natural hazards with engineering, socio-economic and financial processes. Therefore, catastrophe-risk assessment involves multiple disciplines, but is often performed by a limited number of consultancy companies. Mitchell-Wallace et al. [16] give a comprehensive overview of the cat-modelling field, and present flood modelling as primarily related to fluvial (rivers) rather than pluvial (cloudbursts) floods. It has also been stated that floods differ from other hazards in the ability to identify locations susceptible to flood damage at property level, and that attention is turning to smaller-scale protection of individual properties [18].

Cat models require loss data which may not always be at hand for the extreme natural hazards that are often modelled. Data series for a few decades might exist but common metrics for regulators, rating agencies and internal guidelines are usually based on 200- to 250-year return-period losses, which cannot be derived from available data. The cat-modelling methodology allows for a better estimation of extremes without the existence of such loss data. Cat models have other advantages over actuarial methods, traditionally used in the insurance industry, since they can apply changes in the underlying risk, such as hazards changing because of changes in climate, flood defences or infrastructure. On the other hand, its development is limited both by a lacking balance between hazard and vulnerability information and by protective commercial interest preventing the methodology to be openly published in scientific literature. Cat modelling in Sweden has furthermore been very limited.

To close these gaps, this study presents a cloudburst cat model to identify and assess cloudburst-based flood hazards, exposures and vulnerabilities in an urban context. The model, developed within the Splash (Swedish pluvial modelling analysis and safety handling) project, was used to test the hypothesis that a cat model, based only on cloudburst intensity to describe the hazard in combination with high-quality, property-level vulnerability data, could provide reasonable results for three events in the city of Jönköping, south Sweden, thus providing a scalable approach (that can be used from city blocks to whole provinces) that bypasses the complications of hydraulic modelling. Data on pluvial-flood vulnerability is very scarce in Sweden, and there exist, to our knowledge, no data in any scientific peer-reviewed publication on quantitative relations (i.e. vulnerability curves) between pluvial flood hazards and vulnerabilities for Swedish conditions. We are also not aware of any openly published cat-modelling studies of cloudbursts in Sweden.

The goals of this study was two-fold:

1) To develop a cloudburst-flood cat model, based on a simplified hazard module, applicable for areas scarce of critical hydraulic data or resources for hydraulic modelling.
2) To establish a vulnerability curve for cloudburst-flood risks for Swedish conditions, based on the simplified hazard module, and using insurance data to assess damages.

If possible, we also wanted to see if we could detect a change in time of the vulnerability curve as a result of learning and adaptation between the three events and to investigate the sensitivity of the model to quality of the cloudburst input.

2. Background

European countries are subject to significant financial losses not only from the events themselves, but also from flood-risk-reduction strategies and costly structural defences. Effective adaptation strategies are needed, combining flood-protection infrastructure, nature-based solutions, and risk-financing schemes to manage the adverse consequences and buffer their economic impacts [19]. Grahn [10] shows that almost 70% of flood claims to Länsförsäkringar, the largest Swedish insurance group, occurred during June, July and August, which largely corresponds to flash floods caused by cloudbursts. In Sweden, flood damage to private property is automatically covered by basic home insurance [10]. The pricing is not connected to the flood risk in the actual area, and policyholders are not refused flood insurance in their home insurance. To obtain a mortgage on a house, the property must be insured, which implies that the insurance coverage amongst homeowners in Sweden is close to 100%.

Intense rainfall causing those floods is denoted differently but with similar meaning. The term chosen in this article, 'cloudburst', was introduced by Woolley [20] as "… a torrential downpour of rain which by its spottiness and relatively high intensity suggests the bursting and discharge of the whole cloud at once". Alternative terms to describe these intense, short-duration rain events such as 'water bomb', 'torrential rain' and 'down-pour' are commonly utilised [21]. Although the phenomenon has a long history in literature, there is no consistent intensity threshold used to delineate cloudburst events [3].

In Sweden, cloudburst-flood assessment has gained increased attention in the 2010s. Nyberg et al. [6] show that there were in average 45 cloudburst-flood events every summer during 2009–2018 with consequences of different severity. Grahn and Nyberg [10] present insurance claims after 49 pluvial flood events in 13 municipalities in Sweden for the period 2000–2013. Rain amount, intensity and duration are assessed from radar data. The authors report that events with high rain intensity result in substantially higher number of claims than events with a lower intensity even if the daily rain amount is high. Blumenthal and Nyberg [7] investigate the relation between rain characteristics and insurance claims for 111 pluvial-flood events during a 15-year period in the cities of Gothenburg and Malmö. One weather station with high temporal rain-data resolution is used in each city, and the insurance data are aggregated daily at parish (sub-municipal) level for the parishes surrounding the weather station. The key result is a strong correlation between rain intensity (15 and 60 min), and number of claims and total compensation. A combination of high rain amounts during 60 min together with very high intensities during 15 of those 60 min gave extra high explanations of the damages. Sörensen and Mobini [11] used around 5500 insurance claims and data from the municipal water-utility company in Malmö for a 20-year period to investigate mechanisms behind urban flooding. For short-duration events with high rain intensity, the insurance claims are shown to be related to topographic factors such as patterns of overland flow and distance to sewer systems. There is an overrepresentation of claims in areas with combined sewer systems.

In the framework of flood risk, vulnerability is a key component. Despite the increasing amount of studies on flood hazards, in-depth information on vulnerability in Sweden and the Nordic countries is very limited. Additionally, model developers need to implement transdisciplinary approaches, also involving private and public sectors, and particular aspects used for catastrophe-risk assessment may fall outside the areas of each discipline. The lack of reliable data for empirical losses is a big contributor to the overall uncertainty in cat modelling. Insurers normally only store data they find useful for analysis and have historically not stored many exposure and loss attributes that could provide information about the exposure to natural hazards. This is particularly true in the Nordic countries where windstorms rather than floods have been given attention. Windstorms require less spatial detail than floods, thus the spatial detail that satisfies the insurers' modelling needs is normally not enough for flood modelling. As far as we know, the only cloudburst-flood cat model for Sweden is a non-published, commercial product [22].

In Sweden, some municipalities have invested in rain-gauge networks with high temporal resolution. These networks of gauges, in some cases covering large urban areas [23], are the best present resource for cloudburst estimations. The network of the Swedish Meteorological and Hydrological Institute (SMHI) is distributed around the country and most often does not support assessments and modelling in urban areas because of a too-low spatial density. Swedish radar-based precipitation data provide a very low spatial resolution and uncertain local data. Several sources of vulnerability and exposure data are needed. While the spatial resolution and accuracy of geographical exposure data in Sweden and many other countries is sufficient, there is a need for not-so-available qualitative exposure metrics such as building type, basements, occupancies, properties, etc. Since cat modelling requires data on all buildings in a modelled area, the amount can be large. In Sweden, this type of data is available and can be bought from Lantmäteriet (the Swedish mapping, cadastral and land-registration authority) and Metria AB (a state-owned limited company providing geographical information, planning and surveying services, map and real-estate services and geographical analyses).

The city of Jönköping, chosen for our study, was struck by a large pluvial flood in July 2013. During this event that led to much attention and reactions, the regional hospital was flooded. Cloudburst floods, with more than 7 insurance-loss claims for one day, also occurred in 2014 and 2017. One reaction to the 2013 flood was to improve the sewer and stormflow network in central parts of the city [24,25]. This is ongoing work over several years possibly allowing us to see vulnerability changes over time. Jönköping was thus suitable for our study.

3. Study area

The Jönköping municipality, with an area of 1560 km^2, is located in the county of Jönköping and had 142,427 residents in the end of 2020. This corresponded to 39% of the county's and 1.4% of Sweden's total population. The city of Jönköping, the largest urban agglomeration in the municipality, is situated at the southern shores of Lake Vättern, Sweden's second largest lake. The city is a growing economic and cultural centre with about 93,000 inhabitants [26].

The city of Jönköping has a humid continental climate with long cold winters and short warm summers. The mean (2011–2020) annual temperature is 7.0 °C and the mean (2011–2020) annual precipitation is 606 mm/year, approximately 64% of which falls between April and October [27]. The surface-water network in and up-stream the city is dominated by river Tabergsån draining a small (245 km^2) catchment from SW and connecting two lakes centrally located in the city with Lake Vättern. A second watercourse, east of Jönköping, river Huskvarnaån drains another small (664 km^2) catchment from SE. Land use outside of the urban areas is equally represented by forests and agricultural land. The dominant soils outside the city centre are glacial sediments of sand and gravel (south and west), and till soil (east). The lowest and highest points in the municipality lie at 84 m and 351 m above sea level. The difference in elevation is most prominent around the city of Jönköping, located in a bowl-shaped valley with steep slopes surrounding the eastern, southern and western city boundaries. This topography makes the city especially prone to pluvial flooding, whereas fluvial flooding is a small problem. In the insurance-loss dataset provided for this study, six cloudbursts generating 5 or more claims occurred in the period 2002–2017. This corroborates the data of [6] who found seven events in Jönköping for the period 2009–2018. This flood susceptibility and the possibilities to obtain detailed insurance-loss data made us choose the city of Jönköping for the study (Fig. 1; to improve clarity and comparability, the colour coding of the three cloudburst events are the same in Figs. 1 and 4–6).

4. Methodology

This study was based on three methodological pillars (Fig. 2): a multi-source data-collection strategy, spatial analyses, error-correction and reformatting within a Geographical Information System (GIS) (ESRI ArcGIS 10.7 and ArcGIS Pro), and a cat-modelling environment (Oasis ktools version 3.2.1).

5. Data

Data were collected from the insurance company Länsförsäkringar Jönköping, Jönköping municipality, Lantmäteriet and Metria AB (Table 1).

Apart from standard GIS-data processing such as import/export, clipping, resampling, interpolation, spatial and table joins and geometrical calculations, interpolation of rainfall data was given special consideration. The most time-consuming operations were the creation of hazard data in the form of rainfall intensity, matching of taxation values from Metria AB to the building extents and creation of variables coupled to the insurance-loss data. The modelled area (Fig. 1) was selected to include the whole municipal rain-gauge network and damage-claim buildings.

5.1. Precipitation data

We received precipitation data from 20 municipal tipping-bucket gauges, distributed over the study area (Fig. 1). The gauge capacity was 180 mm/h or more. These data were analysed for cloudburst events on July 26, 2013, August 16, 2014, and June 14, 2017.

Precipitation was aggregated in mm for each station on an even 5-min basis during each cloudburst event. A moving-window technique was used to identify the hour with maximum accumulated precipitation per station, in the following named "cloudburst". The cloudbursts for each event were then interpolated with Inverse Distance Weighting (IDW) including all stations with a squared distance exponent to create a continuous rainfall pattern with the spatial resolution of the cloudburst model (50 m). This interpolation took place even if the cloudburst hour was not the same for all stations.

One of the municipal rain gauges, located centrally in the city where much of the damages occurred (Ekhagen, see Fig. 5), recorded

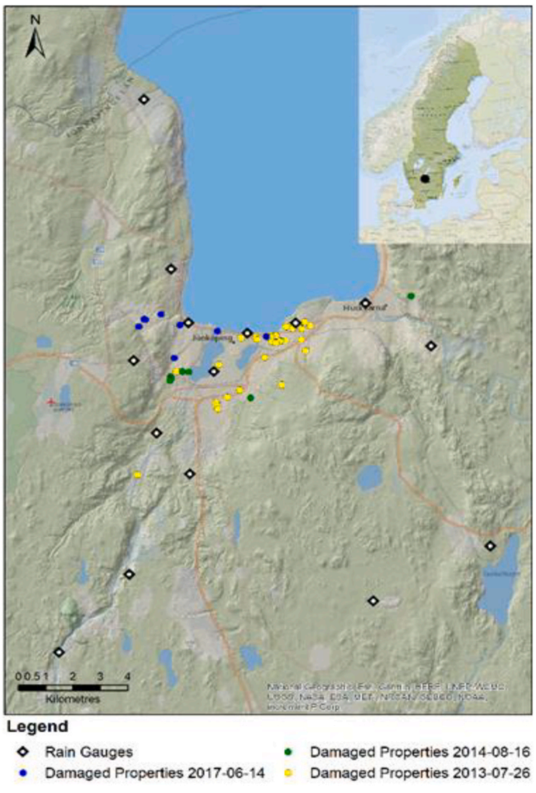

Fig. 1. The cloudburst-modelling area, centred on the city of Jönköping, a rectangle of 427 km^2 divided into 50 × 50 m^2 grid cells during modelling. Also shown is the municipal rain-gauge network and property losses reported to the insurance company Länsförsäkringar Jönköping during three cloudburst events.

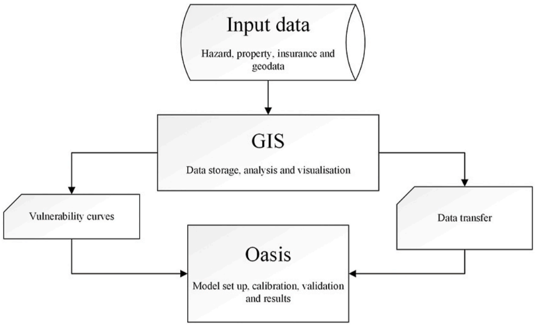

Fig. 2. Methodological framework.

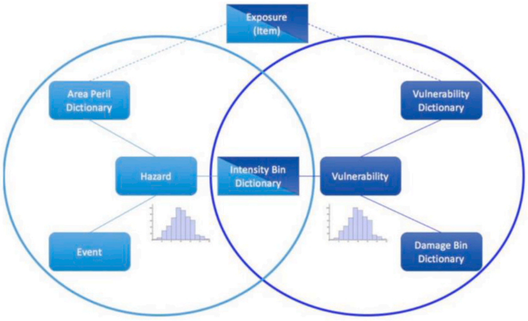

Fig. 3. Overview of Oasis model components showing the coupling between elements describing the hazard (in this study the cloudburst flooding) and the vulnerability (in this study the damage to properties). The exposure in this study is a list of properties at risk (from Oasis Loss Modelling Framework Ltd).

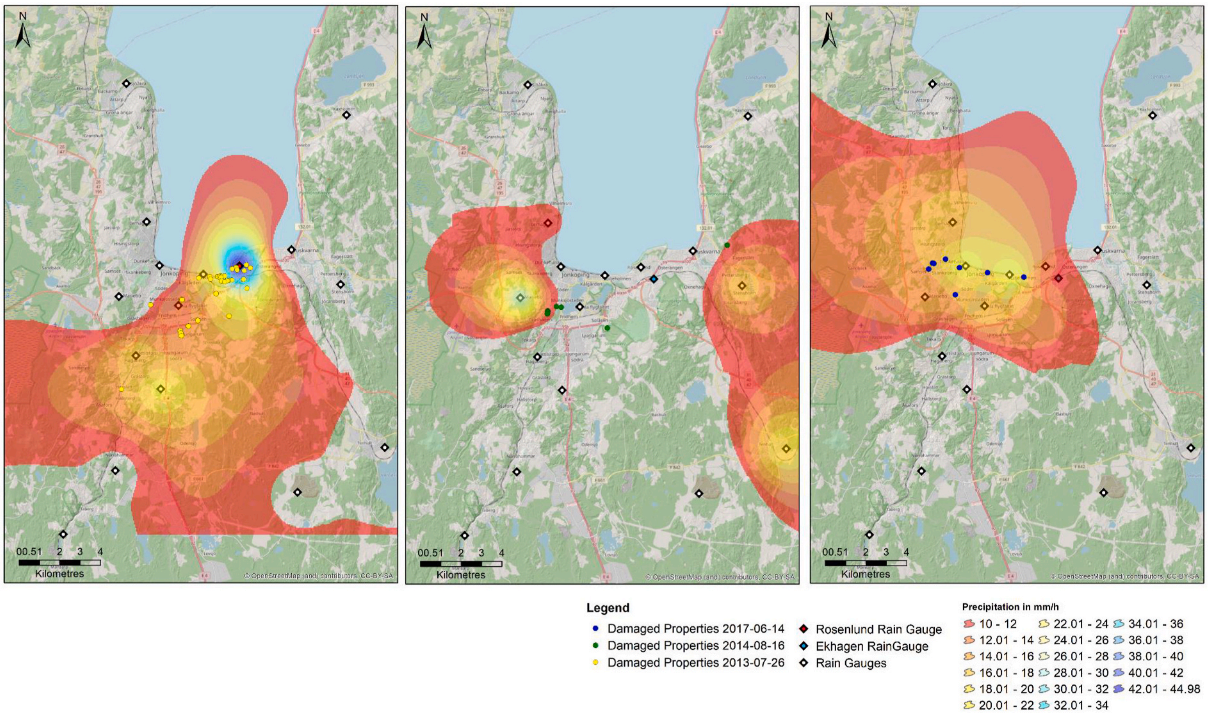

Fig. 4. Cloudbursts (mm) over the modelled area during three events. Damaged properties with insured losses are marked as small circles. Left on July 26, 2013 (yellow damages), centre on August 16, 2014 (green damages), right on June 14, 2017 (blue damages). On the 2013 event, the faulty Ekhagen municipal gauge (green diamond) was replaced by the private Rosenlund gauge (red diamond), maintained by a municipal employee.

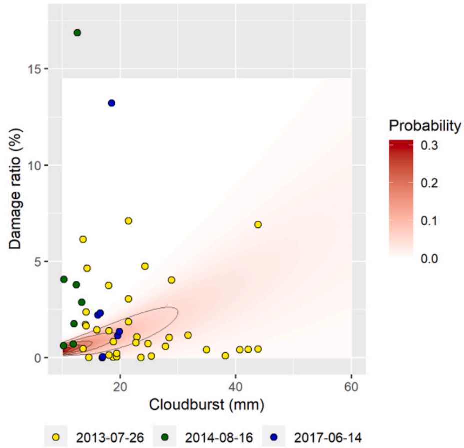

Fig. 5. Conditional vulnerability curve for 37 damage claims in Jönköping resulting from the cloudburst (defined here as hourly rain exceeding 10 mm) events on July 26, 2013 (yellow), August 16, 2014 (green), and June 14, 2017 (blue). Four claims occurred for cloudbursts below 10 mm. The intensity of the red field shows the assumed uncertainty range around the central vulnerability curve. The curve is conditioned on a 2.9% chance of loss being satisfied and adjusted to fit the 2013 event.

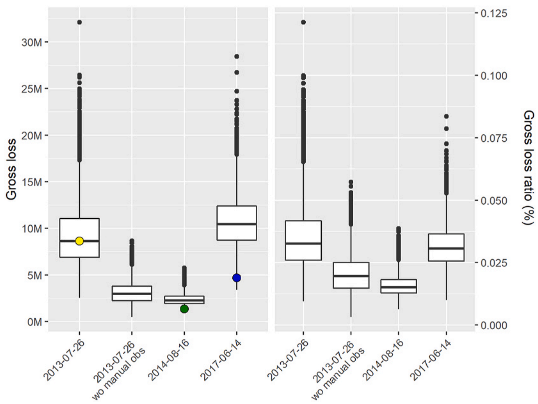

Fig. 6. Insured (gross) losses (SEK) and loss ratios for three cloudburst events. Colour coding as in Figs. 1, 4 and 5: yellow (July 26, 2012), green (August 16, 2014) and blue (June 14, 2017). Results for the 2013 event is based both on cloudburst calculations with the additional private rain gauge and on using only the municipal rain-gauge network ("wo manual obs". The box limits represent the lower quantile Q1, median and upper quantile Q3 respectively, and the dots represents outliers >1.5 * Q3.

Table 1
Data and data providers.

Type	Issued by	Format	Spatial resolution
Insurance-loss data	Länsförsäkringar Jönköping	Excel spreadsheet	On property level
Rain-gauge data	Jönköping municipality	Shapefile (point)	One point per station
Building extents	Lantmäteriet	Shapefile (polygon)	One per building
Property taxation values	Metria AB	Excel spreadsheet	On property level

2.2 mm of rain during the first 15 min of the cloudburst on July 26, 2013 but then stopped recording. In the same area, 68 mm were recorded in 90 min by a private gauge in the garden of a municipal employee. After evaluating the municipal and the private gauge records, the municipality stated that the private record was trustworthy and that the municipal gauge failed [28]. We converted 68 mm per 90 min to 45 mm per hour and then used this value to calculate the cloudburst layer for the 2013 event.

5.2. Location of buildings and values of properties

The locations and extents (given as polygons defining the building's ground-floor plans through exterior walls) of 57,408 buildings in the modelled area were obtained from Lantmäteriet. Unique building IDs, building type and occupancy were also included in the dataset. Taxation values of 24,613 properties were purchased from Metria AB whereas building-taxation values were not available. The matching between building locations and the corresponding property-taxation values required a partly manual methodology and the two attributes had to be used in combination in different parts of the analysis and modelling.

A property can contain one or more buildings with different functions. Our study area contained an average of 2.33 buildings per property. Apart from a unique property identifier, the dataset from Metria AB contained one of 61 type codes per property as an indication of occupancy. Each building in the dataset from Lantmäteriet contained one of 36 type codes for building usage. The code lists did not match 1:1. About half of the building types from the building-extent layer were small complementary buildings, e.g. garden sheds or garages, detached from the main building. The most typical case (around 90%) was that two buildings were connected to one property, i.e., one main building and one complementary building. In these cases, matching was easy since the property taxation value could primarily be attributed to the main building. The matching was done through a unique identifier in the GIS layer-attribute tables. The less typical cases included properties with several taxation units containing one building, or large multi-purpose buildings in the city centre with residential and office units. Matching was also difficult for multiple industrial buildings with equal function in the building dataset, but only one or two taxation units in the property dataset. In all of these cases, a semi-automatic matching approach was used where the analyst was given manual control of the matching process for every case. Thus, the matching process introduced some degree of uncertainty. Fortunately, positional accuracy was maintained in nearly all cases. Even if a few buildings on the same property were attributed mismatching taxation values, the buildings most likely lied adjacent to each other and yielded similar rainfall intensity and other derived values.

5.3. Insurance data

In Sweden, the home-insurance coverage is close to 100% [10]. Länsförsäkringar Jönköping is part of the leading national insurance group Länsförsäkringar with a national market share of around 35% of the home insurance market. Länsförsäkringar Jönköping has a market share of residential policies of around 50% in the Jönköping region. We used flood-insurance data from Länsförsäkringar Jönköping as a proxy for flood damage to establish flood-damage vulnerability curves. Date of damage, insurance type (type of insured property), address, and damage cost were important parameters. Each record in the damage data was identified by address and property designation and we assumed that the main building on each property was responsible for the claim. The original dataset contained 232 reported cases in 2003–2017 of which 55 occurred during the three cloudburst events subject to this study. These were completed with information required by the model, such as coordinates, taxation values and corresponding precipitation data. Of these 55 claims, 40 damages occurred on July 26, 2013, 8 on August 16, 2014 and 7 on June 14, 2017.

Buildings damaged during the cloudbursts on the three days were attributed precipitation values in mm through a GIS overlay function between building extent and rainfall raster surface. The damage ratio was obtained for each damaged property by dividing the loss with the property taxation value in the hazard-affected areas, in cases where the accumulated rainfall over the building extent was estimated higher than 10 mm during the cloudburst hour.

6. Modelling

A cat model consists of a two main components.

The hazard component describes the nature of the hazard, with an intensity metric associated to it. In the case of this study the hazard was cloudburst and the metric was rainfall intensity in mm. Many cat models are probabilistic, based on a large number of stochastic events, designed to represent all the events that would occur during a given time period. The Splash case, on the other hand, is deterministic and based on 3 historical events.

The vulnerability component describes the damages caused by the hazard intensity. Vulnerability-curve methods were originally developed in the USA [29,30] and are today seen as a standardised approach to assess flood damages [31]. Governmental agencies, research institutions and insurance companies in many countries develop and use these curves to assess expected economic impacts [32,33].

The vulnerability curve is normally modelled as a damage ratio [0,1] which describes the damages caused by the hazard. A damage ratio of 0.1 means that the financial costs to repair the building after an event is 10% of the building value prior to the event. Normally a model has different curves depending on exposure characteristics like building materials, construction standards and occupancies. In the Splash case we only developed one curve because of loss-data limitations. Flood-damage vulnerability curves must use the same intensity as in the hazard component, thus curves with different hazard metrics are not interchangeable. Water depth is the most common intensity metric in flood-damage models, whereas the Splash model uses rainfall intensity.

6.1. The Oasis framework

The Splash model is built on the open-source Oasis platform. It is an open-source cat-modelling platform established in 2012, with the intention to standardise cat-modelling data and provide functional model calculation. The Oasis Loss Modelling Framework Ltd is a non-profit company funded by its members, which include a large number of key insurance and reinsurance companies. The framework provides a data standard for inputs and outputs and the needed calculation functionality.

The Oasis calculation engine, ktools is publicly available on GitHub[1] and runs on Linux. Ktools uses two sets of files, static and input (Table 2). The static files provide basic information of the model, like footprints (the area struck by the damaging event) and vulnerabilities (the damage distribution), whereas the input files consist of the case-specific user inputs such as exposure information, and how to aggregate results. All input files are in .csv format. In addition to the files in Table 2, there are a number of files that contain

[1] GitHub Inc. (https://github.com/OasisLMF/ktools) is a US-based global company that provides hosting for software development version control using Git, a distributed version-control system for tracking changes in source code during software development.

Table 2
The two types of ktools files used in the Splash model.

File	Description	Original data source
Static files		
Footprint	Binned hazard information for all modelled events by geographical unit	Interpolated cloudburst data derived from the rain-gauge network in Jönköping.
Vulnerability	Map between hazard intensity and damage bin	Loss data from Länsförsäkringar Jönköping matched with the footprint from the actual events
Damage bin dict	Map between damage bin and damage ratio	
Input files		
Items	List of all properties at risk and their corresponding vulnerability id and geographical unit	Property stock database
Events	List of all events	
Occurrence	Information about occurrence times per event	
Coverage	Property taxation value by item	

information about insurance-specific, financial calculations, as well as reference files not required for the calculations but useful for understanding and analysing the output, e.g., damage ratios and for converting binned values (continuous values discretised into intervals) to actual precipitation amounts.

6.2. Modelling structure

The modelling was based on 632,814 squares (50 m × 50 m, Fig. 1) forming a grid covering an area enclosed by SWEREF99 coordinates: 439744.69, 6387959.10: 472244.69, 6425209.10. Each cell was assigned a cloudburst value based on the interpolation of precipitation-gauge data. The resolution of 50 m is rather low, providing computational efficiency. The cloudburst calculations are relatively simple, making this modelling approach easily scalable. All buildings in the modelled area were considered as point data at the centroid location of the initial building extent, i.e., the centroids were mapped into a cell and the loss was calculated from the corresponding cloudburst values.

The financial modelling in an insurance portfolio can be complex with multiple buildings being covered under the same policy, peril exclusions or peril sublimits. All properties in the Splash model were considered to be covered under individual policies with a default deductible of 10,000 SEK and an unlimited compensation limit. The chosen deductible was the highest possible deductible used by Länsförsäkringar Jönköping for homeowners in 2013. The loss exceeding the deductible for each building sums to an insured loss, or gross amount in Oasis. From a societal point of view, the total economic loss, i.e. loss including the deductible, might be of interest. Therefore, the total economic loss is also calculated under the name "ground-up loss".

6.3. Vulnerability curves

To get the damage ratio for the vulnerability curve, the losses needed to be normalised by the building value but three of the 40 building losses, occurring in the wake of the July 26, 2013 cloudburst event, did not have a value associated with them. They were therefore excluded from the vulnerability-curve fitting. These three cases were all public entities (retirement home, school, and hospital). The hospital was an extreme outlier with an insured loss of 25 million SEK, contributing to more than 80% of the total insured loss. Of the remaining 37 losses, the total insured loss was 4.5 million SEK distributed across occupancies according to Table 3.

Not all buildings exposed to a cloudburst are damaged. For various reasons one building exposed to a given amount of rain may be unaffected whereas another may be damaged. To account for this we introduced a probability-of-loss value, P_{loss}, the probability that a building is going to be affected at a certain intensity. This value is likely to vary between different vulnerability curves and rain intensities. We used a single value for all cases because of the limited number of loss data. P_{loss} was estimated in the calibration to 2.9%. From the data, an approximate probability of loss of around 0.4% could be deduced by combining historical losses from 2013 with current building data and an approximate market share of Länsförsäkringar Jönköping (50%). This number corresponds to the losses reported to Länsförsäkringar Jönköping, thus only the losses that exceeded the deductible. It is not comparable to the 2.9% in the model, which is the total number of buildings damaged regardless of loss amount. When running the model and analysing the modelled losses, the probability of loss exceeding the deductible was approximately 0.6%, the same order of magnitude as the approximate 0.4% probability of loss suggested by the data.

Table 3
Insured and taxation values of the buildings (excluding public property) used to analyse the July 26, 2013 event. The mean loss ratio gives the quotient of loss values over the taxation values for the damaged properties.

Building type according to property database	Taxation value (SEK)	Total insured loss value (SEK)	Number of losses	Mean loss ratio (%)
Single residential	28,987,000	827,509	12	2.85
Unspecified	380,951,000	1,747,569	10	0.46
Multi-residential	193,910,000	1,380,857	11	0.71
Other	47,502,000	583,307	4	1.23
Total	651,350,000	4,539,242	37	0.70

6.4. Computation

The Oasis software can run on a variety of computers, and is developed in a Posix/Linux environment. The Splash model was run on a Windows laptop with the Msys[2] Linux shell.

Since the vulnerabilities were given within an uncertainty band defined by a normal-probability distribution (Figs. 4), 10,000 simulations for each building, on the basis of the cloudburst attributed to it, were done to encompass this uncertainty. The damage-ratio value for each simulation, cloudburst and building was given by the normal-distribution random generator in Oasis, with the buildings treated as fully independent from each other. The average value of the 10,000 results for each building was used as the final modelled result. After calculating the individual losses, the loss amounts from all buildings were aggregated by event and the aggregated damage, or loss ratio was calculated as the aggregated loss values divided by the aggregated property taxation values for the buildings at risk. The comparison between simulated and actual gross loss and gross-loss ratios for the different events were carried out as Box and Whisker calculations [34] in R (version 4.0.3) [35].

6.5. Calibration, validation and sensitivity analysis

Calibration and validation of the model were conducted by comparisons against three historical cloudburst events and corresponding insurance-claim data. Such comparisons require information on: 1) hazard: date, type of event, and hazard intensity; 2) building-claim data: building characteristics; and, 3) insurance-claim data: values. Loss data (40 of 55) from July 26, 2013 were used for vulnerability-curve derivation and calibration whereas the events on August 16, 2014 (8 of 55), and June 14, 2017 (7 of 55) were used for validation.

A simple sensitivity analysis of the model to cloudburst input was possible since one of the municipal rain gauges failed on the largest event, on July 26, 2013. The faulty gauge was replaced by a trusted private gauge for the calibration. A result comparison was then made by replacing the corrected cloudburst field with the original field using the faulty gauge.

7. Results

7.1. Precipitation

The hazard input to the Splash model was the cloudburst intensity over the modelled area (Fig. 4). On the 2013 event, two cloudburst-intensity maxima could be seen. The first over a relatively flat valley bottom where about half of the damaged buildings were located, whereas the second and largest maximum was located along the shore of the lake at the bottom of the steep north-to-west-facing hillslopes. The 2014 cloudburst was located to the west and to the east of the city centre with its maxima on the mountain ridges. The damaged buildings on this occasion were located similarly to the 2013 event, accumulating water from the hillslopes to the west and to the east. During the 2017 event, the largest cloudburst intensity occurred on the western ridge and along the western part of the lake shore at the bottom of east-facing hillslopes. Half of the damages in this case took place at buildings on the hill, close to the maximum cloudburst intensity and the other half at the flat lake-shoreline area below the east-sloping hillside. The vast majority of the damages during all three events thus took place in relatively flat areas where water accumulated from hillslope runoff.

7.2. Vulnerability curve

The vulnerability-curve data, conditioned on the probability, P_{loss}, that a building was affected at a certain cloudburst intensity, were rather scattered (Fig. 5). We used a power function for the conditional vulnerability curve to describe the connection between cloudburst intensity (*i*, in mm during the cloudburst hour) and damage ratio for damaged buildings (*dr*), a normalised loss to be multiplied by a property-taxation value:

$$dr = \frac{i^{1.6}}{7500}$$

The parameter values of this equation were achieved by calibrating the function to the cloudburst event on July 26, 2013. Since vulnerability data are commonly uncertain, the Oasis modelling framework have functionality to include uncertainty around the mean damage ratio for a given hazard intensity. In our case, this is done by applying a normal distribution around the curve with a default variation coefficient of 0.5. As an example, the mean damage ratio is 0.05 for a 10 mm cloudburst so the damage ratio is normally distributed according to $N(\mu = .05, \sigma = .025)$ in this case.

7.3. Model analyses

The calibration to the July 26, 2013 event was successful and allowed the modelled gross loss to match the actual gross average loss (Fig. 6). The modelled losses during the three events differed less than the actual losses, indicating that the major difference between the events was in their geographical coverage rather than in their rain intensities. The simple sensitivity analysis also clarified the very high sensitivity to the cloudburst input. The difference in cloudburst input with or without replacement of one failing rain gauge made the modelled average gross loss to differ by a factor of three! Results from the two validation events show that the actual losses were smaller than the modelled losses, providing an indication of a gradually increasing resilience to cloudburst damages.

The economic consequences to a building from a given precipitation intensity varies a lot both in practice and in the model. The

[2] MinGW (Minimalist GNU for Windows) is a free and open-source software-development environment to create Microsoft Windows applications. A component of MinGW known as Msys (minimal system) provides Windows ports of a lightweight Unix-like shell.

many outliers in the Box-and-Whisker plot in Fig. 6 shows this. It is driven by the large uncertainty in the vulnerability function which is a consequence by the large spread in the historical loss data.

8. Discussion

The large and increasing negative consequences resulting from cloudburst flash floods call for developed and improved risk assessments. Cloudburst events can be catastrophic like in Copenhagen 2011 with damages of around 700,000,000 € [36]. Even if most cloudburst events are smaller in scale, the accumulated loss is still substantial because of the frequency of events. In Sweden only, around 45 events occur every summer, each leading to costs from tens of thousands to tens of millions euros. The randomness in time and space make floods from cloudbursts difficult to assess, predict, and warn for.

While cloudburst-flood events play an important role in flood-risk management, models of them are under-represented in flood modelling. Urban pluvial-flood models are even less common and may directly use measured rain fields to establish runoff volumes and a hydraulic model to assess water levels and velocities [37]. A common way to model pluvial floods is to use a hydrological model to establish runoff volumes and a hydraulic model to assess water levels and velocities [38,39]. Flood-hazard modelling has taken a leap forward, both because of improvements in measurement techniques and data availability such as digital-elevation models and improved modelling tools, such as one- and two-dimensional hydraulic modelling [40]. These tools offer advantages, including differentiation of risk within flood zones, wider coverage and consistency in the quality of the underlying datasets. Nevertheless, flash-flood models and modellers are hampered by the lack of data for model calibration and validation [41]. Moreover, economic impacts of a flood are hardly reproduced by ex-post data, and biases must be accounted for when transferring models between different cases, e.g. insurance conditions, uncompleted claims etc. [42]. These were reasons for us to investigate the possibility of bypassing the traditional way to model the hazard and simply replace it with cloudburst intensity in a flood-damage model.

The Swedish cloudburst cat model presented in this study investigated aspects of model transparency, data availability and data resolution. Private single houses were the risk objects in focus. Our model was built on the Oasis Loss Modelling open platform to increase transparency and benefit from the open-source calculation standard provided by the ktools simulation engine. Oasis provides transparency in the sense that both the data standard, and procedure for loss calculation are open and well documented.

The core of a cat model is the vulnerability curve, connecting cloudburst intensity to building damage. We constructed the vulnerability curve using data from a network of municipal rain gauges, and 37 insurance claims. We used precipitation intensity directly rather than flood-water levels as hazard input. Van Ootegem et al. [9] show this direct approach to explain almost as much of the variation in damages as a water-level approach. A study [7] in two Swedish cities show a strong correlation between intense rainfall and damage to private houses, using spatially aggregated data. The direct cloudburst approach decreases time and knowledge needed to build, run and use the model. A flood-level approach requires a hydraulic model to simulate water levels, based on specific cloudburst and catchment characteristics. Expert competence and data on topography, runoff coefficients, etc. are needed to set up and run such a model, which could be a hindrance to perform a flood-loss analysis for certain contexts and applications. A negative aspect of the direct cloudburst approach is that we bypass knowledge about runoff processes built during decades of flood research. At the same time, it can be difficult to motivate the setup of a complex model for all cities and neighbourhoods that can be damaged by small-scale and short-term runoff processes that characterise a flash-flood event.

In an early-warning perspective, the direct use of cloudbursts as driver in a flood-loss model can be motivated since the lead time is short to carry out an analysis during an acute situation. Furthermore, the establishment of a return period for a rain event of a certain intensity and duration is more straight-forward than to establish a return period for a water level resulting from a rain event combined with a multitude of runoff factors.

All cat models, and this model specifically, are subject to many uncertainty factors: model-structure uncertainty, parameter uncertainty, and uncertainty in data for input, calibration and validation. The Oasis platform supplies a few tools to deal with the input- and calibration-data uncertainty, but this only partially addressed the two factors we believe caused the greatest uncertainties. Firstly, the model was very sensitive to cloudburst input and this uncertainty can only be remedied by a sufficiently dense network of rain gauges with high time resolution. Development in merging public and crowdsourced private rain data could be one way to achieve better cloudburst input [43]. Future improvement could also come from the development of IoT sensors [44], and combinations of gauge and radar data [45].

Secondly, the availability of individual insurance-claim data is very limited. The loss from the historical event on July 26, 2013, used as a base for the calibration, was in fact less severe than the event on June 14, 2017, when looking at the hazard. The fact that one individual loss, at the hospital, contributed to more than 80% of the total loss of 30 million SEK makes it questionable whether this event represents the loss from an average event of this magnitude. The vulnerability curve was calibrated on only 37 individual damages and the plot clearly shows the uncertain scattered behaviour of these losses. There is thus no statistical significance behind the vulnerability calibration. This was not surprising, though, considering all other factors apart from rain intensity that affect the damage ratio at single properties. We had access to a total of 55 insurance claims, including different house types, different flood types (from surface flow, sewer system, etc.), and the statistical analysis did not allow us to divide the data set into sub-groups. It is also worth mentioning that the EU GDPR directive makes the use of insurance data very complicated, which drastically reduces the data availability in flood studies. There might be several reasons to choose to aggregate the data used in a vulnerability curve. One is to reduce the uncertainties and noise brought in by all those factors that we do not control. The result from [7] point in that direction. Another reason would be to convince the insurance sector that their data could be part of flood analysis without violating any integrity or competition regulations.

We also realised that the action taken by the municipality to improve the storm water and sewer system the years after the first big event in 2013 affected damage levels for the two following events and subsequently the vulnerability curve. We could see a lower level for the accumulated damages for the 2017 event, compared to the two previous events. This could be an adaptation effect, resulting from updated and improved storm-water-drainage capacity although more data is needed to corroborate this hypothesis.

The data used for this model approach was rain data with high temporal resolution from a municipal network of gauges, claims data from one insurance company, and property values for all buildings in the city of Jönköping. It would be a short step to develop this model into a general tool, useful for assessments of urban cloudburst-flood damages. In a proactive mode, the model can be run using a design rain event with a certain return period. Data on rain characteristics, based on public high-resolution rain gauges are often publicly available. The vulnerability curve developed in this study certainly needs additions from further studies, and cannot be said to be general for all geographical contexts. The experience from, e.g. the Hazus model in the USA [46,47] shows that a set of vulnerability curves are needed for different conditions and this is most likely the case also for the type of urban flash floods that follow from cloudbursts. The third type of data used, the value of 24,613 properties, a big and costly effort in our project, could be simplified based on statistics for a number of "type cities". The adaptation factor, mentioned above, is a reason why vulnerability curves should be seen as dynamic rather that static, calling for regular updates. This is not, however, only a problem for cat models but for all models affected by changes in the catchment characteristics.

9. Conclusions

- It is possible to get acceptable results from a cat model for cloudburst flooding using only rainfall, and not surface-water level as driving variable. This could open up for such loss modelling in places where complex hydraulic modelling cannot be done because of lacking data or skill of responsible staff.
- Loss data are increasingly difficult to access at property level. Our vulnerability curve, based on real property-level data, could possibly be a benchmark for theoretically derived curves.
- It is uncertain to derive vulnerability curves based on aggregated loss data, so the database from this study (more than 57 thousand buildings, 232 inundation damages and high-quality geographical data) can prove valuable for detailed research into the physical causes of cloudburst inundation damages. For operational purposes, the model could be simplified with respect to input data on cloudbursts and property values, and used with aggregated damage data when individual damage data are not available.
- The lowered loss levels between three consecutive cloudburst events indicate that vulnerability curves might need to account for increased risk awareness and preventive measures after a major event.
- Results are sensitive to both temporal and spatial resolution of the input rainfall field. Cloudburst cat modelling would specifically benefit from denser rain-gauge urban networks, e.g. through new IoT technologies or crowdsourced data.

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.

Acknowledgement

This study was part of the Splash project (2018–19) aimed at introducing cat-modelling methodology in Sweden and to develop research on rainfall hazard, exposure and potential damage. The project intended to develop a reliable method to manage insurance data on flood damages, to better understand the relationship between precipitation and damage, and finally to establish an arena for collaboration between academia, insurance businesses and rescue services to reduce long-term disaster risk in Sweden. The authors want to thank the funders of this study: the Swedish Knowledge Foundation (Contract No. 20170183) and Karlstad University. This study was made possible by the trans-disciplinary collaboration among the Splash-project partners: Swedish Fire Protection Association, Guy Carpenter & Co. Ltd, Länsförsäkringar Jönköping, Länsförsäkringar Insurance Group, Jönköping Municipality, Oasis Loss Modelling Framework, and Karlstad University. We acknowledge the Oasis Loss Modelling Framework Ltd for the right to reproduce Fig. 3.

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