

THE ADDED BENEFIT OF 3D BUILDING STRUCTURE FOR FLOOD RISK ASSESSMENT

A review and application to The Netherlands



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Abstract

Flooding represents one of the most frequent and disruptive phenomenon affecting several million people globally each year. Climate change is increasing the frequency and intensity of flooding events putting urban areas at greater risk. For these reasons, assessments on the potential damages from flooding to building assets could in theory help policymakers supporting the right mitigation actions through spatial and economic information on the exposed assets at risk. The inclusion of structural attributes other than building footprint for flood risk assessments has been limited. This study research through the available literature about the current role of geometrical building attributes such as footprint, height and volume for natural hazard models with a focus on flood risk analysis. It compares a traditional 2D flood risk assessment to a 3D model for The Netherlands which also accounts for a building's height.

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1. Introduction and Problem Statement

1.1 Natural Disaster Risk

Human-induced climate change events such as hot extremes on land and in the ocean, heavy precipitation, drought and fire weather have caused extensive impacts on the life of ecosystems and humans (IPCC, 2022). Since 1990, natural hazards have produced more than 1.6 million casualties globally with average estimated losses around USD 260–310 billion per year (Ward et al. 2020). The increase in global temperatures to 1.5°C above pre-industrial levels is expected to cause more frequent and intense climate hazards with a high degree of certainty (IPCC, 2022). These predictions are extremely important for the sustainability of urban areas as they are the centers of economic activity and the location where most people live. Human and physical assets such as land, infrastructures and buildings could potentially be more vulnerable to damages from the expected increase of natural disasters' intensity and frequency. For these reasons, modelling the risk from natural hazards could be a crucial tool for policymakers as it provides useful information for the selection of mitigation and adaptation strategies. Among the natural hazards, flooding represents one of the most frequent and disruptive phenomenon affecting several million people globally each year (Jongman et al., 2012). From 1980 to 2013, floods losses amounted for more than USD 1 trillion and caused at least 220 000 fatalities globally (Hendry et al. 2019). Sea level rise projections combined with storm surge and heavy rainfall will increase the risk of flooding in coastal areas (IPCC, 2022).

1.2 Problem Statement and Research Questions

Generally, natural disaster risk assessment can be expressed as the product of hazard, vulnerability, and exposure (Ward et al. 2020, Houston et al., 2011). Exposure represents the assets at risk, such as land, infrastructures, buildings and population (IPCC, 2022; Tierolf et al., 2021; Zhi et al., 2020). To date, the majority of studies have assessed natural hazard exposure as a function of build-up area, expressing the value of physical assets as per unit of area of land use class (Paprotny et al., 2020). However, the 3D pattern of cities, i.e. including the height of buildings, is also an important determinant of urban environmental impacts but this information has often been neglected for natural hazard risk assessments. The exclusion could be partially due to the lack of information on the different attributes of buildings such as floor space area, height and volume which are not homogeneously available (Li et al., 2020; Paprotny et al., 2020).

Additional attributes on structural assets other than the buildings' footprint could potentially provide a better assessment for various natural hazard risk. Röthlisberger et al. illustrate how 3D building information could be valuable for flood risk assessment (2018). Models based on a building's surface area led to an underestimation of the exposure values suggesting that accounting for the building's volume could produce better results (Röthlisberger et al., 2018). Until recently, the majority of the studies assessing urban flood risk have done so by representing it as a function of the buildup area (Kubal et al., 2009; Waghwalā & Agnihotri, 2019) and beside few studies which have

accounted for the height and volume of buildings (Zhi et al., 2020; Amirebrahimi et al., 2016), there is limited knowledge on how to incorporate 3D building information into a flood risk assessment. For these reasons, the primary objective of this research is to perform a systematic literature review on the role of 3D building structure for flood risk assessment with a focus on exposure. Based on the findings of the literature review, a demonstration of the concepts is conducted through a GIS application on The Netherlands. The aim of this research is to ultimately try to answer the following main and sub questions:

- What is the influence of building's footprint (2D), height or volume (3D) on exposure to urban flooding risk?
 - How does building's footprint influence flood risk?
 - How does building's height or volume influence flood risk?
 - What is the difference between a 2D and a 3D flood risk assessment?

2. Theoretical Background

2.1 Definition and Drivers of Flooding

“Flooding is the temporary inundation of all or part of the floodplain or temporary localized inundation occurring when surface water runoff moves via surface flow, gutters and sewers” (Cirella & Iyalomhe, 2018). There are two main types of flooding: river and coastal (Ward et al., 2020). Flooding could come from a river or other body of water such as oceans and it results in damages to assets. The increase in volume within a water body causes the latter to exceed drainage channel capacity and overflow its boundaries. Many elements drive flooding ranging from natural to anthropogenic causes and often acting in synergy. Four key drivers have been identified for urban flooding: climate and meteorological events, poor urban planning, urbanization and anthropogenic activities (Cirella & Iyalomhe, 2018). Each main driver is characterized by additional sub drivers. First, an important cause of urban flooding are climate and meteorological events. These events are a function of seasonal and short term rainfall as well as changes in the climate, micro-climate and the weather pattern such as heavy storms and tidal influence. Second, poor urban planning is another important aspect of the urban flood system and it is caused by the lack of well-designed draining facilities, the development on floodplains and exceeds design criterion. Third, urbanization plays an important role as increasing the impervious area, modifying the land cover and depleting the ecosystem ultimately lead to a higher probability of flooding. Finally, anthropogenic activities must be accounted in the form of construction or blockage of drainage facilities, violations of local building regulations, failure to regard flood warnings and the dumping of debris into the drainage system (Cirella & Iyalomhe, 2018). All these drivers ultimately contribute to the scale of the impacts from urban flooding. The impacts are numerous and range from social losses such as death tolls, to direct

and indirect economic damages to buildings and their contents (Duan et al., 2016). This research focuses on the potential economic losses of buildings that are exposed to flooding.

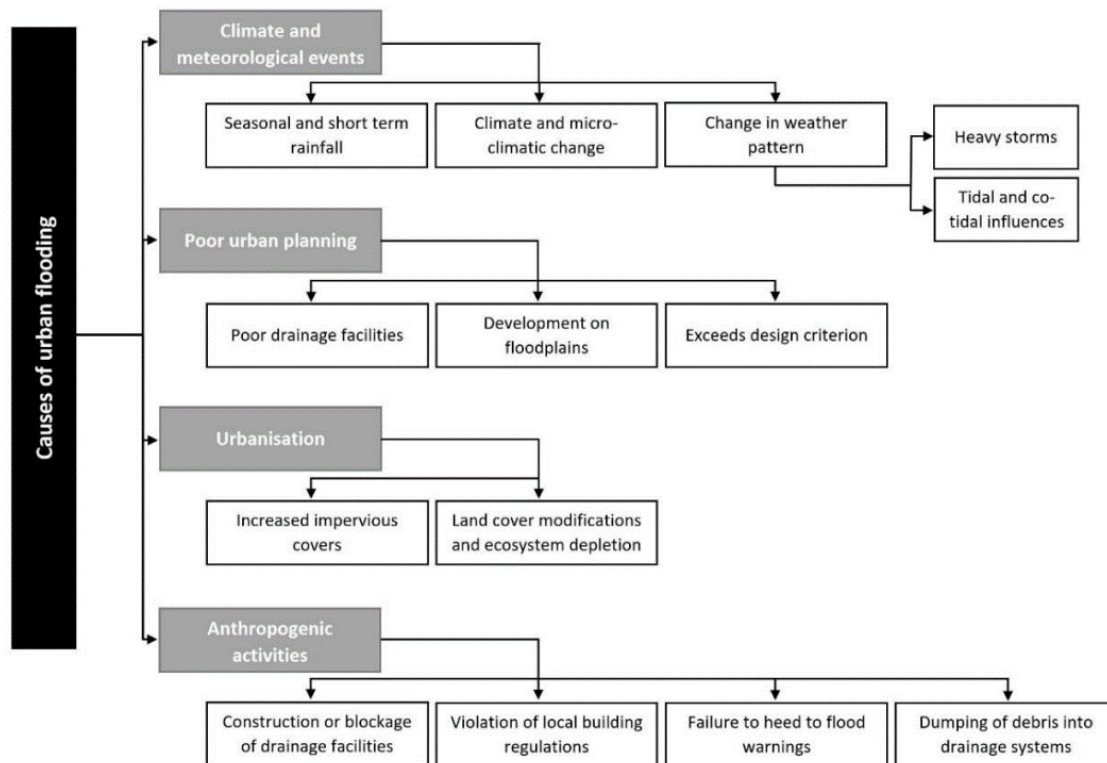


Figure 1. Conceptual framework of urban flooding drivers (Cirella & Iyalomhe, 2018).

2.2 Flood Risk Assessment

The Sendai Framework expresses risk assessment as the product of hazard, vulnerability, and exposure (Ward et al. 2020; Tierolf et al., 2021; Röthlisberger et al., 2018). Flood risk is quantified using the following equation:

$$\text{Flood risk} = \text{Hazard} \times \text{Exposure} \times \text{Vulnerability}$$

Hazard is the probability of an hazardous event happening in a place, including risk factors and disaster environment. For flooding, this refers to the event itself, including its characteristics and probability of occurrence (Ward et al., 2020). In flood risk assessment, hazard is modeled through flood extent or inundation maps. This is done considering historical flood data and future probability of hazard's occurrence.

Exposure represents the location of economic assets or population at risk of flooding. Exposure can be mapped using a population or a land-use approach. Built environments vary depending on their locations as they could range from villages to megacities. Urban landscapes have distinct characteristics regarding building area, volume, intensity and density (Ward et al., 2020). These unique features could potentially affect exposed assets value from flooding (Röthlisberger et

al., 2018). Assets exposure is traditionally estimated in monetary values with different methods (Paprotny et al., 2020; Röthlisberger et al., 2018)

Vulnerability refers to the function of the potential damage from the hazard to a specific target, such as population density and buildings (IPCC, 2022; Tierolf et al., 2021; Zhi et al., 2020; Luu et al., 2020). In flood risk assessment a single depth-damage curve or intensity-damage function (IDF) is often used (Tierolf et al., 2021; Ward et al. 2020). This curve describes graphically the relationship of the damage expected to result at a specified depth of flood water. The function is commonly used for building assets where the stage or depth describes the level of water inside a building and the loss indicates the damage expected from that depth of water (Huizinga et al., 2017).

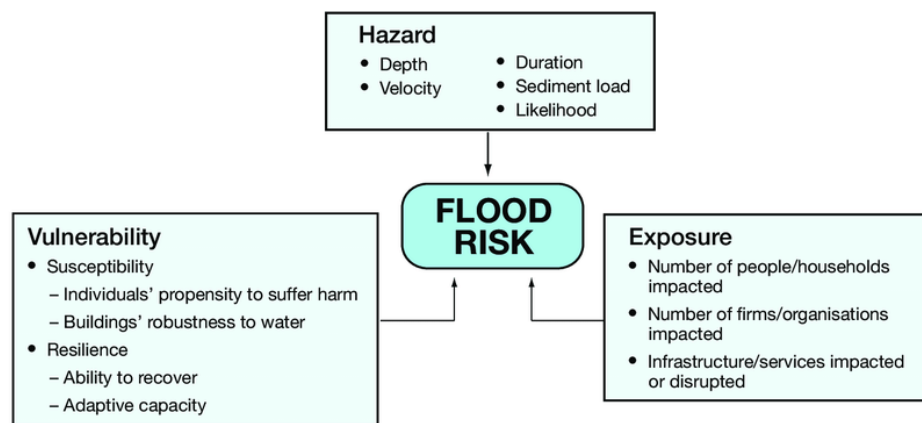


Figure 2. Conceptual framework of flood risk (Houston et al., 2011).

As illustrated by Ward et al. (2020), different indicators have been selected to quantify risk from flooding namely direct and indirect damage, affected people, GDP, fatalities and exposed assets.

Based on the Sendai Framework, total exposure values for building assets could potentially be calculated as a function of their 2D or 3D attributes. The proposed formula is presented as follow:

$$\text{Total Exposure} = \text{Building Attribute} \times \text{Damage}$$

Total Exposure refers to the monetary loss value of all buildings exposed to flooding. Building Attribute is the total area or volume of the exposed assets affected by flooding, expressed in m^2 or m^3 respectively. Damage describes the monetary value associated with the loss of buildings and their content per unit of attribute and is expressed as Euro per m^2 or m^3 .

3. Methods

This research aims at answering the main question and sub questions by initially conducting a systematic review of the current available literature on buildings' exposure to flood hazards. Exposure is investigated as a function of the following structural attributes: footprint, height or volume. The review is expected to provide an overview of how 2D and 3D building structure are applied on current

assessments of exposure to flood hazard. In particular, the search is focused on the current application of building's footprint, height or volume for damage function assessments. The goal of this review is to find applicable numerical monetary values or parameters of the damages per unit of building's area or volume. Based on the findings, an application of a 2D and a 3D damage function is conducted for The Netherlands, total exposure is calculated and subsequently the results are explored. The outcomes of this application are used to answer the main research question and sub questions.

3.1 Literature Review

The literature review is used to assess current global application of 3D building structure for natural hazard. The aim is to identify a numerical monetary value or function of the damage to buildings as per unit of area and volume. The main foreseen problem of this research refers to the aim to gather data on 3D building structure for flood risk assessment. As mentioned in the problem statement section, until recently there has been a lack of available data regarding the height and volume of buildings. As a result, it is expected that few studies exist on flood risk assessment as a function of different structural attributes other than build-up area. For these reasons, the literature review is expanded to a global scale and to other natural hazards in order to maximize the probability of finding relevant data on damage and its applications. In addition, to increase the possibility of obtaining useful data, two methods are applied: a Web of Science database search and the snowballing of the results from the literature review. For the database search, the following table describes the selection criteria.

Table 1. Criteria used for the literature review search

Criteria	Inclusion	Exclusion
<i>Language</i>	Papers in English	All other languages
<i>Sample area</i>	Global	
<i>Date</i>	All years	
<i>Natural Hazards</i>	Primary: river and costal floods; Secondary: tropical cyclones, wildfires, earthquakes, tsunamis, landslides, volcanos, droughts	
<i>Data quality</i>	Peer reviewed literature	Unless no other data can be found, grey literature like reports from organizations and newspaper are excluded

<i>Database</i>	Web of Science	
<i>Variables</i>	Total buildings' exposure, buildings' footprint/height/volume, buildings' damage per unit of footprint/height/volume	
<i>Search Scope Keywords</i>	3D building, footprint, height, volume, floor, risk, exposure, value, flood, urban flood, river flood, costal flood, flood risk assessment, hazard, vulnerability, annual damage, vulnerability curve, damage curve, natural disaster, natural hazard	

The following search string is used in the Web of Science database to find peer-reviewed scientific journals in English:

(("3D" OR "building" OR "footprint" OR "height" OR "volume" OR "risk" OR "exposure" OR "Depth-Damage") AND ("flood*" OR "tropical cyclones" OR "wildfires" OR "tsunamis" OR "landslides" OR "volcanos" OR "droughts") AND ("Damage") AND ("Floor*" OR "basement")).

Röthlisberger et al. (2018) represents a key paper for this research as it provides an alternative method for accounting buildings' exposed values, shifting away from the traditional approach of solely including 2D data i.e. surface area. Specifically, it illustrates how accounting for buildings' volume rather than area in estimating exposed building values to flood risk provides better results. For this reason, Röthlisberger et al. (2018) constitute a valuable start for applying a snowballing technique, tracking down references or citations in the document. This method is further applied on the results of the literature review as it is possible that a specific paper contains references that have valuable information within the scope of this research.

The results from the two literature review methods are collected and illustrated in a table, i.e. Literature Review Results Table (Table 2). Each paper included in this table is described with different attributes namely research's title, authors, year of publication, hazard type, a short summary of the paper, 2D or 3D, resolution, damage description and model used. The results included in the table are both qualitative and quantitative in nature.

Table 2. Literature Review Results Table

Title	Authors	Year	Hazard	Summary	2D	3D	Resolution	Damage Description	Model

3.2 GIS Application

Along the European coasts, the North Sea region is projected to experience an higher risk of extreme sea levels (ESLs) and flooding (Vousdoukas et al., 2017). Although, there is an extensive literature on urban flood risk assessment at the global scale (Lyle & Mills, 2016; Waghwala & Agnihotri, 2019), fewer studies exist regarding the Netherlands (Koks et al., 2015; Kim & Newman, 2019). Based on the results of the literature review, dataset for the assessment are gathered for The Netherlands. A representation of the results in the form of several maps are made using Geographical Information System (GIS) tools for The Netherlands. The maps include a visualization of total building exposure to flooding as a function of 2D and 3D information.

The paper “Review Article: Natural Hazard Risk Assessments at the Global Scale” by Ward et al. (2020), provides different methodologies on assessing natural disaster risk. Among all the proposed flooding assessment methods, Jongman et al. (2012) offers a first estimation of global economic exposure to both river and coastal flooding for the period 1970–2050, as a function of land-use area subject to 1/100 years flood events. This methodology framework provides a good start and it is adjusted for this paper to fit a 3D model as well.

The GIS application can be described though 5 main steps (Figure 3):

1. Extract flood hazard map with a 1/100-years return period
2. Classify which buildings are exposed to flooding
3. Calculate total value of exposed building attributes for a 2D and 3D model
4. Apply damage functions from the literature review
5. Total exposure maps for 2D and 3D model

1. Extract flood hazard map with a 1/100-year return period

To assess hazard, a digital map depicting flood prone areas with a 1/100-years return period is applied. The dataset is from Dottori et al. (2016) and is freely available online on the European Commission JRC website (the dataset can be found here: Joint Research Centre Data Catalogue - Flood hazard map of the World - 100-year return pe... - European Commission (europa.eu)). The map shows the water depth in meters at a spatial resolution of approximately 1 km.

2. Classify which buildings are exposed to flooding

The objective of this step is to georeference urban land exposed to flooding for The Netherlands. The output of this process is a digital map illustrating which residential buildings area situated within flood-prone areas. Data on European land use is extracted from the 2018 CORINE Land Cover (CLC) inventory, available as a raster map for free on the Copernicus’ website (the dataset can be found here: <https://land.copernicus.eu/pan-european/corine-land-cover>). From the CORINE dataset, residential urban land is extracted for the study area and is classified under

residential. Through a GIS software, the flood hazard map is overlaid on the urban land use map to obtain which residential building areas are potentially being exposed to flooding.

3. Calculate the values of exposed building attributes for a 2D and 3D model

In this step, the values of exposed building attributes are calculate for a 2D and a 3D model. For exposed residential buildings, their footprint and height are calculated. The dataset on buildings is taken from Li et al. (2020) with a raster spatial resolution of 1 km². The dataset includes information on buildings' footprint, height and volume. The CORINE Land Cover (CLC) inventory used in the previews step helps to identify which areas are of residential nature and which are not as the Li et al. (2020) does not make this differentiation. For a 2D model, the value is expressed as the mean surface area of the exposed residential assets, while for the 3D model the value indicates the mean height of the residential buildings.

4. Apply damage functions from the literature review

The exposed urban area (2D) and height (3D) values found in the previous step are used to further categorize the residential building class. Since the 2D model focuses only on the footprint of the buildings and there is a lack of information on their height, a further classification on the types of residential structures is limited. For this reason, urban land classes for the 2D model cannot be further categorized. On the contrary, the 3D model accounts for the height of buildings and this information can be used to further classify building types based on the number of floors. In their research, de Bruijn et al. (2015) set the ceiling height from the floor of residential buildings to 2.5 meters and for each additional floor 2.5 meters is added. The same assumptions hold true for this study and are used to assess different building types. For each building class, namely ground floor, first floor and higher floors, a specific damage function is assigned which are all obtained from the literature review. The results of the calculations are expressed in millions of Euro.

5. Total exposure maps for 2D and 3D model

The final products of this GIS application are few digital maps, similar to the ones in Tierolf et. al (2021) for The Netherlands for a 2D and 3D model. Both maps explain the spatial distribution and intensity of the total damages to the exposed assets from a flood hazard with a 1/100-years return period.

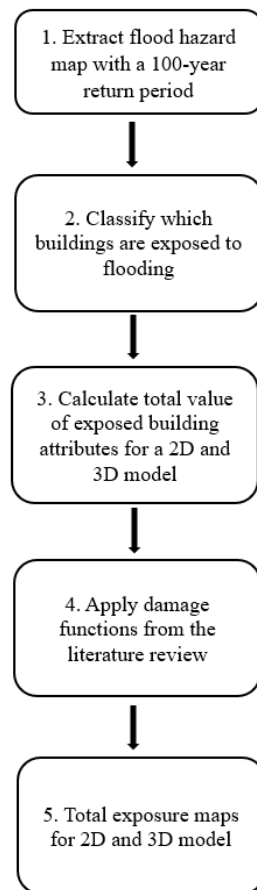


Figure 3. Framework of the GIS application illustrating the flow of the methodology through the 5 main steps.

3.3 Study Area

The Netherlands is an European country located in north-western Europe with overseas territories in the Caribbean. It is the largest of the four countries of the Kingdom of the Netherlands (Aruba, Curaçao and Sint Maarten). The Netherlands is divided in twelve provinces, and it borders with Germany to the East, Belgium to the South, with a North Sea coast-line to the North and West. It shares maritime borders with both countries and with the United Kingdom in the North Sea. Amsterdam, Rotterdam, The Hague and Utrecht are the four largest cities in the Netherlands (Statista, 2022). The country has a population of 17,735,200 and a population density of 423/km² (CBS, 2022). The total surface area of the Netherlands is 41,865 km² or 4.2 million hectares, including both inland and open water. About half of this surface area is destined for agriculture purposes, around one third is allocated to nature, water or recreation with a rather small part of the country (13 percent equaling to 0.4 million hectares) covered by buildings and roads (CBS, 2022). The Netherlands has a low elevation and a flat topography, with only about half of its land greater than 1 m (3.3 ft) above sea level, and approximately a quarter below sea level. In addition it houses more than 8.0 million homes (CBS, 2022).

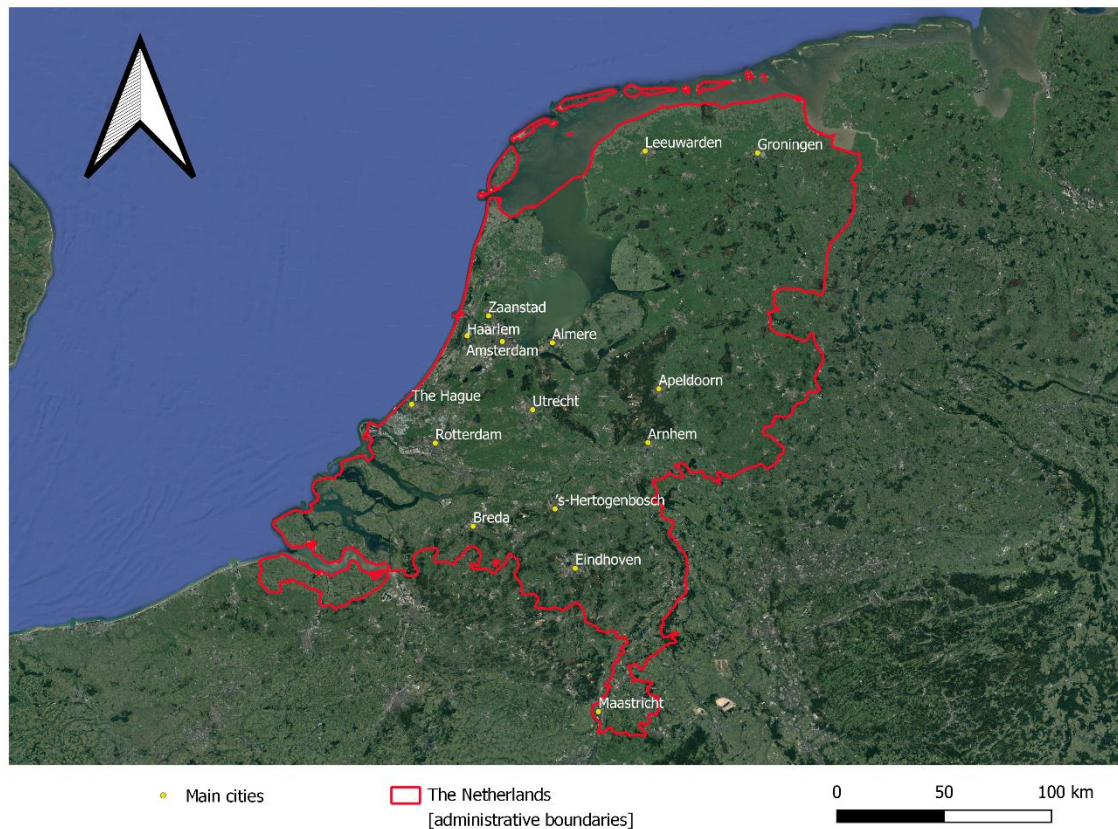


Figure 4. Satellite image of The Netherlands (data acquired from the Google satellite, 2022).

4. Results

4.1 Literature Review

The results of the literature review are shown in the table below (Table 3) and include 11 studies that incorporate the vertical dimension of buildings within their methodologies. Based on the results, the HAZUS model is the most used flood assessment methodology applied in flood risk analysis which also accounts for the 3D aspects of building. The model uses different depth-damage curves for different building categories, differentiating the classes based on their usage, building material, number of stories and basement presence.

The Dutch model HIS-SSM/SSM2015 also divides residential classes based on their vertical dimension but with a different approach compared to the US HAZUS model. In the HIS-SSM/SSM2015, residential buildings are classified into 4 classes based on their floor height: single family houses, ground floor, first floor and higher floors apartments.

The results of the systematic review also include applications of 3D building structure behind flood risk assessments as it is found in the earthquake risk model GEM. GEM makes use of a building taxonomy to group different building classes and for each it assigns a vulnerability curve. This type of approach could potentially have positive ramification for other natural hazard risk assessments.

Table 3. Literature Review Results Table

Title	Authors	Year	Hazard	Summary	2 D	3 D	Resolution	Damage Description	Parameter	Model
1. A comparison of building value models for flood risk analysis	Röthlisberger et al.	2018	Flooding	The paper focuses on the relevance of building value estimation schemes within flood exposure analyses on regional to national scales	X	X	10 km ²	Uniform average value per building volume: Total building value is divided by the total building volume (CHF/m ³). Parameters values are gathered using the portfolio data of insurance companies for buildings which includes the replacement value and volume of virtually every building within a specific area. The total building value is expressed as the sum of all replacement costs of buildings.	648.45 CHF/m ³ per volume above ground (M2)	N/A
2. Multi-hazard Loss Estimation Methodology Flood Model Hazus-MH Technical Manual	FEMA	2009	Flooding	Hazus is designed to produce loss estimates for use by federal, state, regional and local governments and private enterprises in planning for risk mitigation, emergency preparedness, response and recovery. Hazus comes complete with methodology to analyze earthquakes, flood and hurricane winds. The methodology deals with nearly all aspects of the built environment, and a wide range of different types of losses	X	X	Building level	Damage is assessed through different depth-damage curves for several building classes. Residential building classes are divided based on the vertical characteristics of a building, such as the presence of a basement or the number of floors. Estimation of direct damage to the general building stock (percent damage to structures and their contents) is accomplished through the use of readily-available depth-damage curves, compiled from a variety of sources	Specific based on the building class type	HAZUS

<p>3. A review of flood damage analysis for a building structure and contents</p>	<p>Marvi, Morteza T.</p>	<p>2020</p>	<p>Flooding</p>	<p>The review paper provides an insight into flood damage analysis for residential, commercial, and industrial building structure and contents</p>	<p>X</p>	<p>Building level</p>	<p>Depth-damage function (percentage of building value per feet of water). The vertical dimension of buildings is accounted through various depth-damage functions describing different types of structures. Examples include damages to structure and content of one, two or more stories residential buildings with or without basements. Damage is described as the percent of the structure value (damage ratio) to the depth of water relative to the first floor</p>	<p>Specific based on the building class type</p>	<p>HAZUS</p>
<p>4. Using the Hazus-MH flood model to evaluate community relocation as a flood mitigation response to terminal lake flooding: The case of Minnewaukan, North Dakota, USA</p>	<p>Cummings et al.</p>	<p>2012</p>	<p>Flooding</p>	<p>The study uses the Hazus-MH MR4 flood model to examine potential lakeshore flood damages in the city of Minnewaukan, USA from potential future increase of the water surface elevation</p>	<p>X</p>	<p>Building level</p>	<p>Damage is assessed based on the value of residential and commercial Buildings. Residential values are collected from the Tax Assessor for the City of Minnewaukan and used to assess the single value of properties. The damage assessment takes into consideration the vertical dimension of buildings by including a basement level and assuming that all the residential properties in the area have a one. It calculates the exposed assets value as follow: RES1 building value per structure = structure area * (value per unit area, adjusted for the Consumer Price</p>	<p>Specific based on the building class type</p>	<p>HAZUS - MH MR4</p>

								Index * county modification factor) + basement area * (basement value per unit area, adjusted for the Consumer Price Index * county modification factor)		
5. Detailed assessment of structural characteristics of Turkish RC building stock for loss assessment models	Bal et al.	2007	Earthquake	In this paper, geometrical, functional and material properties of the building stock in the northern Marmara Region, particularly around Istanbul, have been investigated and evaluated for use in loss estimation models and other types of statistic- or probability-based studies.	X		Building level	Geometric building characteristics such as height are considered in the damage estimation. Vulnerability is assessed as a function of the different properties of floor. The number of stories of a building is used to define specific building classes and their damage potential	Not applicable for this study	DBELA and HAZUS
6. Development of a probabilistic earthquake loss model for Iran	Motamed et al.	2018	Earthquake	The study identify the regions within the country of Iran with the highest risk, the most vulnerable building classes, and the expected economic losses for a number of return periods	X		Building level	Following the GEM Building Taxonomy, residential buildings are grouped into 23 classes. The model accounts for the height of a building as an indicator to define the different classes within the Iranian region. For each building class a fragility curve is assigned which leads to an estimate of the damage per building class.	Not applicable for this study	EMME and GEM
7. Updated and improved method for flood damage assessment: SSM2015 (version 2)	de Bruijn et al.	2015	Flooding	The report discusses the updated and improved method for flood damage assessment in the Netherlands. It provides depth-damage functions	X	X	Building level	Depth-damage functions per building class. Flood damage is calculated by multiplying the maximum flood damage per object with a damage factor which depends on	Average construction costs (from StatLine database) for residential buildings	HIS-SSM SSM2015

				on different building classes also accounting for the vertical dimension of the structure (number of floors)			the water depth (and other flood parameters). The 3D aspect is included as the report proposes different damage functions based on the height of buildings. For residential buildings, this differentiation only makes a distinction between 1, 2, 4 and 6 or more floors. The exact height of residences can be crucial information in a damage model as residences in high rise buildings often suffer much less damage than ground floor apartments	are: 1000 €/m ² and 260€/m ³ (2011 price level)		
8. HAZUS-MH Flood Loss Estimation Methodology. II. Damage and Loss Assessment	Scawthorn et al.	2006	Flooding	This paper reports on the damage and loss estimation capability of the HAZUS-MH Flood model. It includes depth-damage functions for different building types	X	X	Building level	Depth-damage functions per building class: percentage (%) of the replacement cost of buildings per depth of water in feet. The HAZUS Flood Model uses the Federal Insurance Administration's (FIA) "credibility weighted" depth-damage curves and selected curves developed by various districts of the U.S. Army Corps of Engineers (USACE) for estimating damage to the general building stock. The vertical dimension of buildings, expressed in the number of stories, is reflected in different damage curves	Specific based on the building class type	HAZUS

<p>9. A Probabilistic Displacement-based Vulnerability Assessment Procedure for Earthquake Loss Estimation</p>	<p>Crowley et al.</p>	<p>2004</p>	<p>Earthquake</p>	<p>This study proposes a method that defines the capacity of a building class by relating its deformation potential to its fundamental period of vibration at different limit states and compares this with a displacement response spectrum</p>	<p>X</p>	<p>Building level</p>	<p>Damage to a structure is assessed based on the type of building class it belongs to. To define the different building classes, the study uses different parameters, namely construction material, failure mechanism and number of stories. For this reason damage is a function the 3D aspect of a building such as the number of stories</p>	<p>Not applicable for this study</p>	<p>FORM</p>
<p>10. Flood Depth-Damage Functions for Built Environment</p>	<p>Pistrika et al.</p>	<p>2014</p>	<p>Flooding</p>	<p>The paper aims at demonstrating a step-by-step methodology for devising depth-damage functions using data from a flood event which occurred in Moschato, Greece in July 2002. It also compares the developed depth-damage functions to functions from other areas with similar conditions</p>	<p>X</p>	<p>Building level</p>	<p>Damage is assessed based on different type of building classes. The study presents three types of flood affected buildings: one-story, one-story with basement and basement. Each class</p>	<p>Specific based on the building class type</p>	<p>The Curve Fitting Toolbox in MATLAB</p>
<p>11. Establishment of flood damage function models: A case study in the Bago River Basin, Myanmar</p>	<p>Win et al.</p>	<p>2018</p>	<p>Flooding</p>	<p>This study develops flood damage function models based on the relationships between flood inundation parameters and damage-aggravating factors for two land use categories: residential and agricultural for</p>	<p>X</p>	<p>Building level</p>	<p>Houses in the residential areas are sorted by their plinth height and classified into three different types: one-story, two-story, and stilt. class damage curves are derived based on survey data on historical flood losses.</p>	<p>Specific based on the building class type</p>	<p>N/A</p>

				the Bago River Basin region in Myanmar						
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Based on the results from the literature review, a GIS application is conducted for The Netherlands, specifically on the country's residential buildings.

4.2 GIS Application

From the systematic search, valuable information regarding depth-damage functions is collected and applied for a 2D and 3D model. For the 2D model the proposed depth-damage function for The Netherlands is taken from Huizinga et al. (2017) and it is applied to the building footprint (Figure 5). The average maximum damage value reported in the study is 717 €/m² for The Netherlands (for the year 2010 and not currently corrected for inflation). For the 3D model, the proposed depth-damage functions are extracted from the standard method SSM2015 by de Bruijn et al. (2015) and they take into account the 3D element of structures as the study differentiates buildings based on the number of floors. Contrary to the traditional way of assessing damage, the exact height of a building can be a crucial information in a damage model as residences in higher floors also sustain losses if the level of water reaches a certain depth (de Bruijn et al., 2015). For this reason this assessment takes into account the number of floors of residential buildings and it assigns three different damage-functions with respect to their floor levels. The three residential classes are ground, first and higher floors buildings. In the SSM2015 the physical damage to the structure of buildings is assessed by multiplying the surface of the living space per structure with a value of 1000 €/m² representing the average construction costs for a residence build in the period 2009-2012 in the Netherlands.

Since one of the objective of this study is to compare the application of the two different methods, 2D and 3D, also by exploring the numerical and geographical results from the GIS application, a decision on the adoption of a common parameter as a maximum damage value has to be made. The two models use different approaches to express damage through their functions, with the 2D model showing a numerical value for each depth of water and the 3D model as a percentage of the maximum damage, or damage factor, for discrete water depth. This analysis proposes to use the 717 €/m² maximum damage value contained in the JRC method and use it as the corrected maximum damage value for the HIS-SSM functions ($717 \text{ €/m}^2 = 1$). For this analysis, a maximum damage value for residential buildings of 717 €/m² is applied for both 2D and 3D models (Huizinga et al., 2017). This decision is based on the fact that the 717 €/m² value is from a study published by the European Commission and the JRC technical reports has been used as a consistent resource in the global flood risk assessments community.

The maximum damage value is then multiplied by a damage factor that is dependent on the depth of water from the flooding event, ranging from 0 to 1 where 1 represents the maximum construction value (Figure 6). The depth-damage functions describe this relationship.

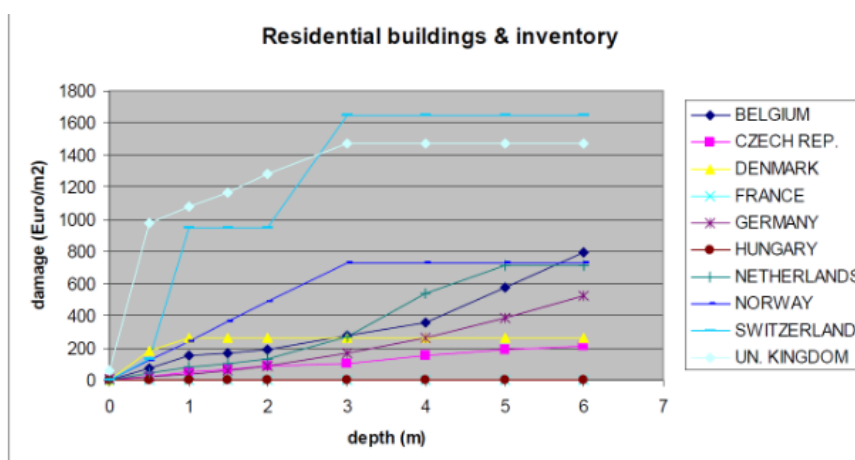


Figure 5. Depth-damage function used in the 2D assessment from Huizinga et al. (2017).

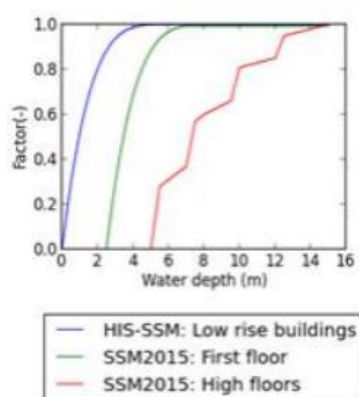


Figure 6. Depth-damage functions used in the 3D assessment from de Bruijn et al. (2015).

From the depth-damage graphs illustrated in the Huizinga et al. (2017) and the de Bruijn et al. (2015) studies, tables for a 2D and 3D model are constructed for the Netherlands describing the damage at discrete water intervals. Since the studies do not provide numerical functions, for the GIS application a reclassification using the QGIS “r.reclass” tool is necessary to translate the damage intensity in relation to the water depth and is reported in the following tables.

Table 4. 2D Model Depth-Damage Discrete Classes Table

Water Depth (m)	Damage (Euro/m ² .)	GIS Classification
0	0	0 meters is equal to 0
1	100	Between 0 and 1.5 meters is equal to 100
2	150	Between 1.5 and 2.5 meters is equal to 150

3	300	Between 2.5 and 3.5 meters is equal to 300
4	500	Between 3.5 and 4.5 meters is equal to 500
5	717	Between 4.5 and 5.5 meters is equal to 717
6	717	More than 5.5 meters is equal to 717

Table 5. 3D Model Depth-Damage Discrete Classes Table

Low Rise Buildings (0 - 2.5m)		
Water Depth (m)	Damage Factor	GIS Classification
0	0	0 meters is equal to 0
0.5	0.2	Between 0 and 0.75 meters is equal to 0.2
1	0.4	Between 0.75 and 1.25 meters is equal to 0.4
1.5	0.6	Between 1.25 and 1.75 meters is equal to 0.6
2	0.8	Between 1.75 and 2.25 meters is equal to 0.8
2.5	1	Between 2.25 and 2.5 meters is equal to 1
First Floor (2.5 - 5m)		
2.5	0	2.5 meters is equal to 0
3	0.2	Between 2.5 and 3.25 meters is equal to 0.2
3.5	0.4	Between 3.25 and 3.75 meters is equal to 0.4
4	0.6	Between 3.75 and 4.25 meters is equal to 0.6
4.5	0.8	Between 4.25 and 4.75 meters is equal to 0.8
5	1	Between 4.75 and 5 meters is equal to 1
High Floors (5m +)		
5	0	5 meters is equal to 0
6	0.3	Between 5 and 6.5 meters is equal to 0.3
7	0.4	Between 6.5 and 7.5 meters is equal to 0.4
8	0.6	Between 7.5 and 8.5 meters is equal to 0.6
9	0.7	Between 8.5 and 9.5 meters is equal to 0.7
10	0.8	Between 9.5 and 10.5 meters is equal to 0.8
12	0.9	Between 10.5 and 12.5 meters is equal to 0.9
14	1	More than 12.5 meters is equal to 1

The respective depth-damage functions are applied to the 2D and 3D models. The results are show in the two maps and tables below.

The following maps are the results of the GIS application for the Netherlands. Figure 7 and Figure 8 below represent mean area and height of residential buildings over a 1km² pixel resolution.

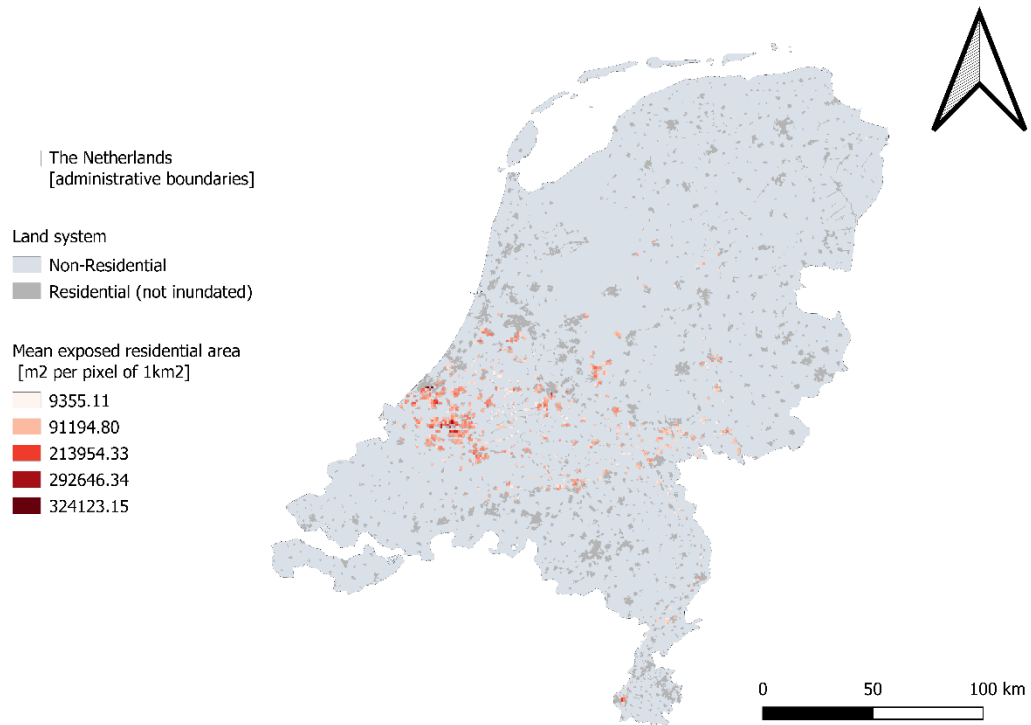


Figure 7. The Netherlands mean area of residential buildings exposed to flooding. The dataset is from Li et al. (2020).

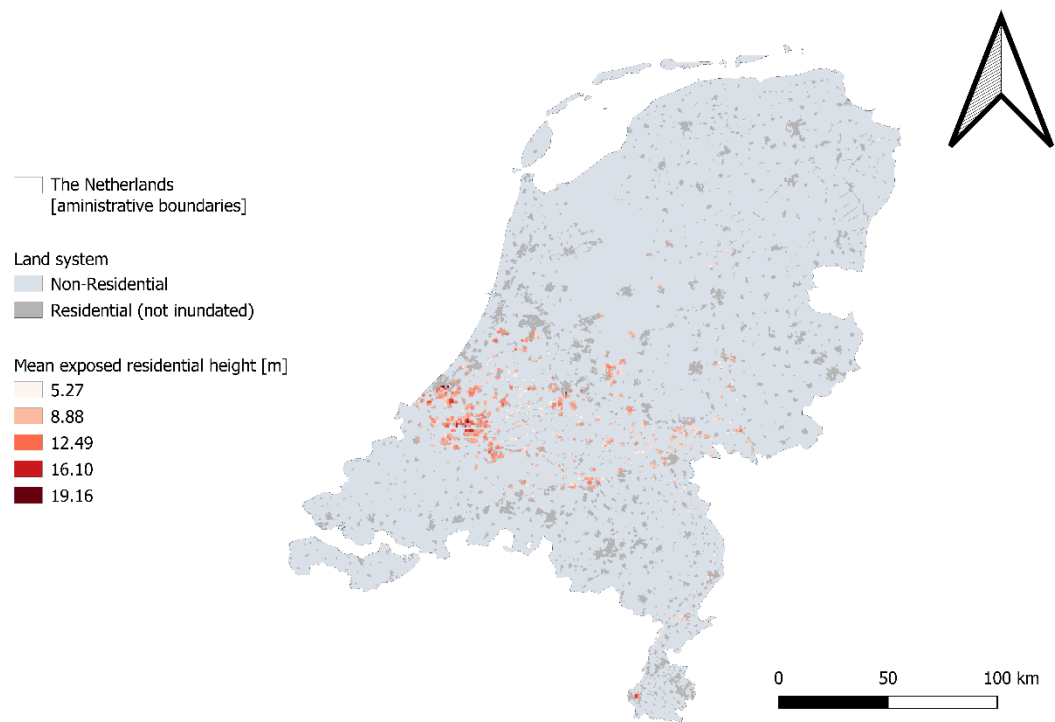


Figure 8. The Netherlands mean height of residential buildings exposed to flooding. The dataset is from Li et al. (2020).

The results from the 2D and 3D model are presented in Figure 9 and figure 10 respectively. Both maps illustrate the total damage to exposed residential assets from a 1/100 years flood event.

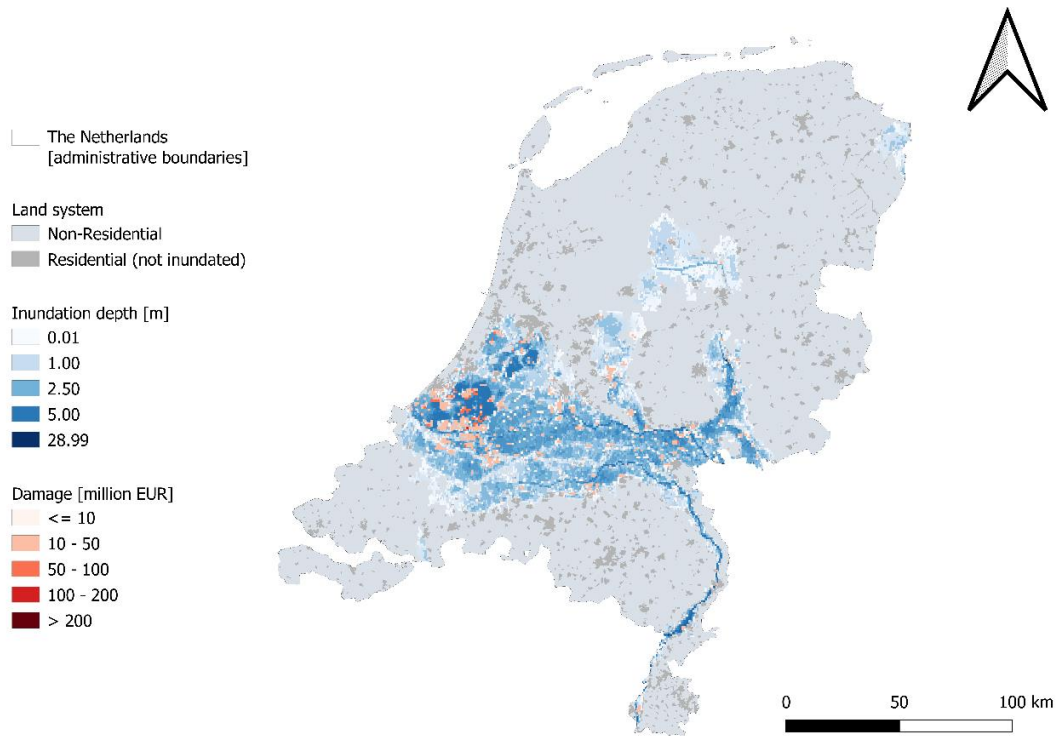


Figure 9. Estimated maximum flood damage 2D map of residential buildings in The Netherlands. The inundation map is based on Dottori et al. (2016).

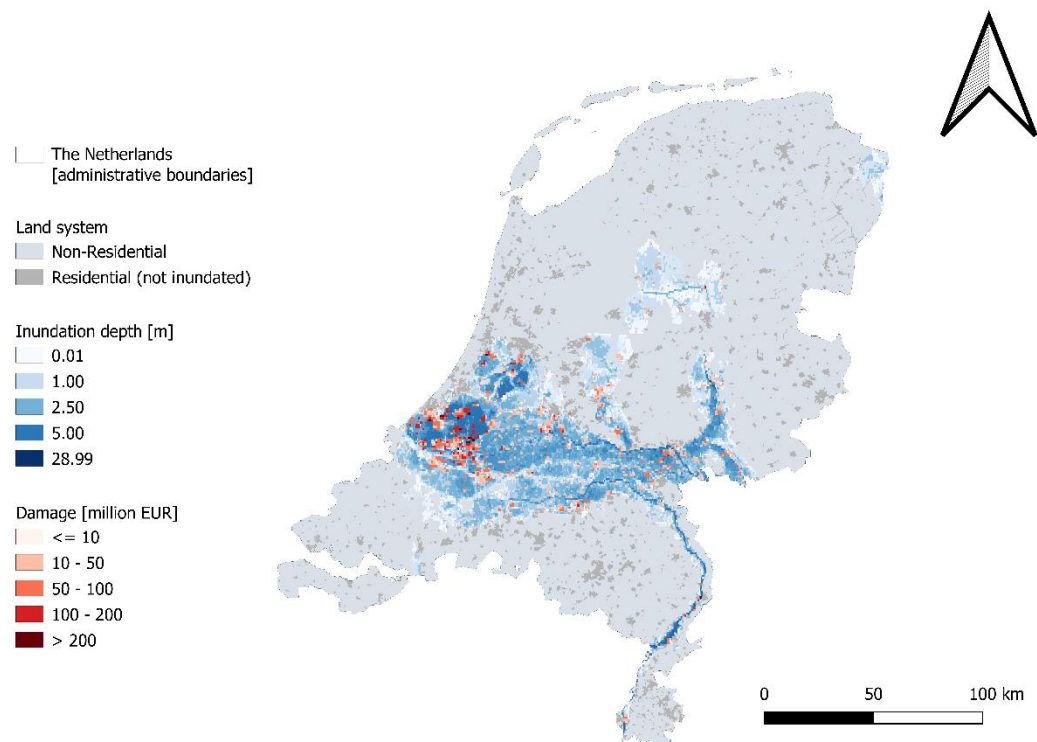


Figure 10. Estimated maximum flood damage 3D map of residential buildings in The Netherlands. The inundation map is based on Dottori at al. (2016).

Based on the 2D and 3D model map results above, a comparison between the two model is illustrated for an area in the Rotterdam/The Hague region.

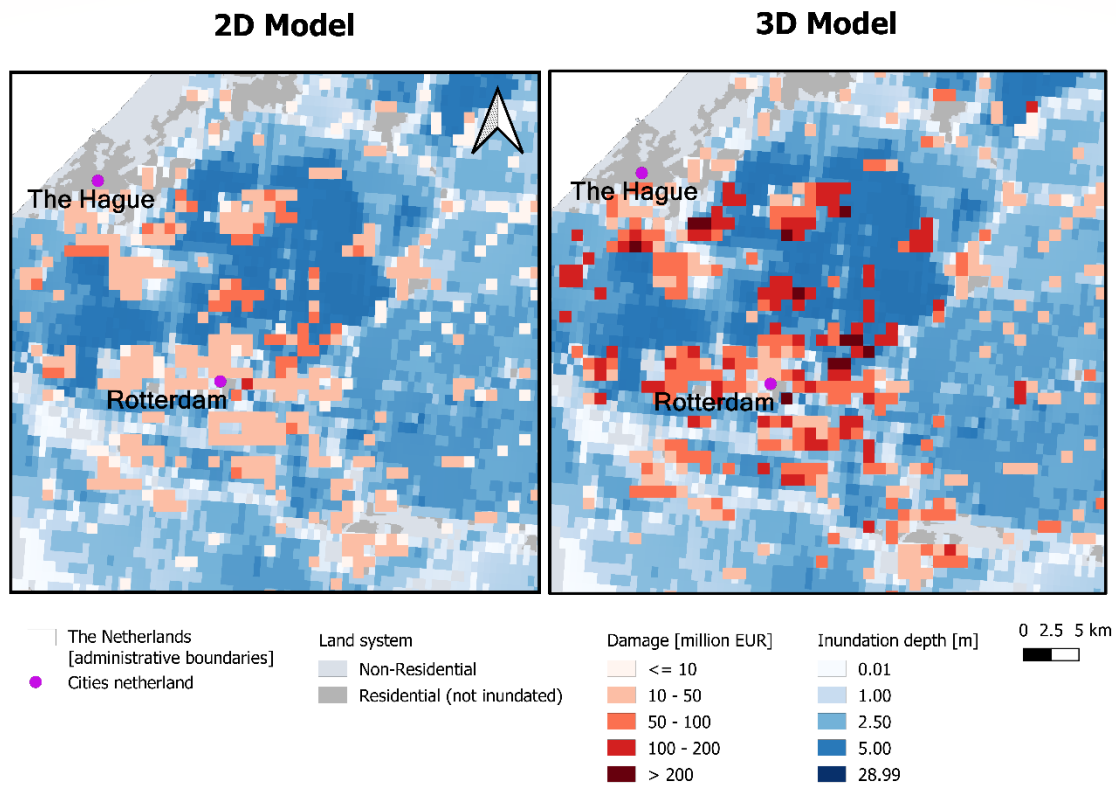


Figure 11. Comparison of 2D and 3D model damage values for the exposed residential buildings in the Rotterdam/The Hague region.

From the GIS application, meaningful statistics are gathered and presented in the following tables. The values for the 1/100 flood event are reported as follow:

Inundation values (Dottori at al., 2016)	Depth of water [m]
Maximum value	28.99
Minimum value	0.01
Range	28.98
Sum	32659.58
Mean Value	1.981

Statistics from Li et al. (2020) are illustrated next which are descriptive for all the residential buildings exposed to the 1/100 years flooding event:

Exposed residential buildings (Li et al.2020)	Footprint [m ²]	Mean Height [m]
Maximum value	359097.375	19.161
Minimum value	9355.106	5.272
Range	349742.269	13.889
Sum	85933723.361	7799.714
Mean Value	95164.699	8.638

For the 3D model, the damages for the exposed residential assets per discrete building class is calculated and reported as follow:

Damage to building classes [million EUR]	Ground Floor	First Floor	Higher Floors
Maximum value	191.067	241.574	277.81
Minimum value	1.983	14.915	32.538
Range	189.084	226.659	245.272
Sum	27993.608	19387.999	6835.679
Mean Value	40.279	100.456	20.381

Lastly, the cumulative damage is calculated for both 2D and 3D model and the total losses are reported below:

Total damage to residential buildings [million EUR]	2D Model	3D Model
Maximum value	148.248	277.810
Minimum value	0.976	1.983
Range	147.212	275.828
Sum	14695.74	54217.287
Mean Value	17.228	55.204

5. Discussion

Most of the studies assessing urban flood risk measure damage as a function of a building footprint. As the JRC model shows, urban flood risk is assessed by multiplying a damage value that describes the intensity of a water event by the footprint of the exposed asset. The 2D model application for The Netherlands indicates that locations with the highest footprint values also share the highest damage values as well as the highest water depth. By looking at the different maps, as the water level and footprint increase so is the value of urban risk damage. These results seem to be consistent for both models. As for the exposed residential building height, the tallest buildings are also located in the same areas of those with the highest footprint values. The 3D model acts in a similar manner to the 2D model as most of the high damage values are registered in those areas in The

Netherlands with larger mean height values. This positive relationship could potentially be explained by the role of a building height in the calculation of damage. In fact, for the 3D model, the total exposed area of a structure, which is multiplied by a depth-damage value, is the sum of the surface area of the ground, first and high floors of a building. Higher exposed area values could potentially lead to higher damages.

The literature review results represent the few works available in which the 3D dimension of buildings is included in the assessment of urban flood risk. In particular, among the numerous models for assessing flood risk, HAZUS and HIS-SSM/SSM2015 propose two methods which accounts for the vertical dimension of a building. Both models in fact include this aspect by proposing different depth-damage curves for different building classes based on the number of floors above ground (both) and underground, such as a basement level (HAZUS only). The JRC model measures flood risk by accounting for a building's footprint, suggesting that damage only occurs at the ground floor and does not make any distinction on the different residential building classes (only for building materials). Both the HAZUS and HIS-SSM/SSM2015 propose a different approach. As mentioned above, by offering different depth-damage curves based on the number of floors, HAZUS and HIS-SSM/SSM2015 equally acknowledge that damages not only occur at the ground level of a building, as the JRC seems to suggest, but that even higher floors and basements are exposed and vulnerable.

The results of the inundation dataset taken from Dottori et al. (2016) have a range of 28.98 meters, with a minimum value of 0.01 meters, a maximum value of 28.99 (close to the city of Gelderland) and an average water height of 1.98 meters. Although the minimum value seems to be in line with a 1/100 years flooding event scenario, the maximum value casts doubts as it does not seem to be realistic. This could be due to errors within their model or analysis. However, for the sake of transparency it is also included in the assessment.

As previously stated in the methodology, this paper set the ceiling height from the floor of residential buildings equal to 2.5 meters and for each additional floor 2.5 meters is added. Taken from the Li et al. (2020) dataset, the results for The Netherlands, show a minimum value of approximately 5.3 meters, a maximum of 19 meters and an average value of approximately 8.64 meters. Based on this statistics, even the minimum pixel value has at least a ground and a first floor. In addition, maximum and minimum pixel value for mean footprint in the Netherlands are 359097.37 and 9355.10 square meters respectively, with an average area of 95164.7 square meters.

Both the 2D and 3D maps show that the areas with the highest water depth in The Netherlands could potentially be the ones located in the South-West region of the country. Rotterdam, Nieuwerkerk aan den IJssel, Zoetermeer and South of The Hague could be the areas most susceptible to a 1/100 years flooding event according to the Dottori et al. (2016) data. In addition, the area of Roermond in the South-East region of the country could potentially be another hotspot. With regard to

the spatial distribution of exposed-building values, both 2D and 3D models show uniform results. In contrast, the absolute values of the GIS application for the two different models lead to different outcomes. The total damage value to residential buildings for the 2D model amounts to approximately 15 billion Euro while for the 3D model the value is equal to almost 55 billion Euro. The 3D model value is approximately 3.69 times greater than the one seen for the 2D model. In addition, for the 3D model, the minimum and maximum damage values are 1.98 and 277.81 million Euro compared to the 0.98 and 148.25 million Euro for the 2D model. Minimum and Maximum values for the 3D model are respectively 2.03 and 1.87 times more than the ones observed in the 2D model. The maximum value for the 3D model could be observed within the high floor building class while the minimum is at the ground floor. Also for the 3D model most of the damage to residential buildings happens at the ground floor level (52%) with first and high floors damage representing approximately 48% of total cumulative damage.

This larger difference in damage values between the two models could be attributed to different reasons. First, as both models' calculations are based on direct damages per meter square of residential area, for the 3D model the overall total area for a building is greater as it includes at least ground and first floor. As mentioned previously, all buildings within the study area have at minimum ground and first floor. As the total area of an exposed building increases due to the inclusion of the above floors of a structure, so is the potential damage from flooding. For this reason, including a building's height in a flood risk assessment could potentially lead to higher total damage values. Second, the two models use unique depth-damage curves which have different slopes meaning they reach the maximum damage at different values. For the 3D model curve, maximum damage could potentially be reached 3 times if the building has multiple floors and the water depth is high enough. In this case, the total damage value of the exposed building would be the sum of the maximum damages for the ground and first floor plus the damages to the higher floors, as this approach is based on floor levels. In addition, the two models differ as the maximum damage for a 3D model is set at water depth values of 2.5, 5 and 12.5 meters, while for the 2D model is set at 5 meters. The large differences in damage values from the two models (the 3D model total damage value is 3.69 times greater than the 2D model) is consistent with the results from the literature and this study adds to the list of work highlighting the uncertainties surrounding the use of general depth-damage curves for flood risk assessments (Wagenaar et al., 2016). As pointed out in their research, Wagenaar et al. (2016) show that the resulting uncertainties in estimated damages are in the order of magnitude of a factor of 2 to 5. The explanation could be found in the implicit assumptions of flood damage functions and maximum damages which can have large effects on damage estimates. On this matter, a careful approach from the flood risk analyst is recommended when choosing a vulnerability curve as well as more research is needed to decrease the uncertainties related to depth-damage functions and maximum damage.

Within the scope of this study, the results show that the area most affected by the 1/100 years flooding event is located in the South-West region of the country. This information could be valuable as it provides a better understanding of where most of the mitigation actions could potentially be taken place and the possible upper cost of inaction. Furthermore, the addition of a vertical dimension within flood risk calculations could potentially emphasize extreme values detection as it is shown graphically for the Rotterdam/The Hague region (Figure 11). Between the two models, the 3D assessment seems to show potential to better highlights the spatial distribution of these areas and assets of high damage values compared to a traditional 2D model.

Finally, this application could be additionally improved by the use of higher resolution data which could in theory achieve more accurate results. Advanced research on flood damage functions and maximum damage parameters could lead to more precise damage estimates. Since flooding is a complex natural phenomenon which has different drivers and impacts depending on a specific environment, including higher resolution data on local conditions and assets could further strengthen a flood risk assessment. These includes, for example, DEM data, the inclusion of installed protection measurements such as dikes, drainage systems, building insured value, number of floors and the building usage to name a few. Local assessments of flood risk, on a city scale for instance, could potentially be more valuable than a large scale analysis as they could consider more elements within the analysis that would be otherwise too complex to assess on a larger scale. Flood risk assessments mainly focus on the damage as a function of the depth of water but other factors could be considered in the estimate as also water velocity and the presence of debris are believed to have an impact on the magnitude of the damage to a specific asset. In addition, the literature seems to be in disagreement on the level of depth of water necessary to make a building collapse. This could be due to several aspects such as the flow velocity of water and the presence of debris, the duration of the flooding event, the construction material of structural walls and of the foundations, as well as local geological conditions (de Bruijn et al., 2015). The HIS-SSM/SSM2015 model suggests that the threshold of flow velocity that is necessary for a building to collapse is equal to 2m/s for single family house and 8m/s for high rise apartment buildings. If water velocity exceeds these values the building is expected to collapse and a maximum damage factor of 1 is assigned to the structure. In contrast, the HAZUS model reports a threshold flow velocity equal to 1.7 m/s at 6 m of water and 2.5 m/s at 3 m of water depth. More research on this subject is need and although it is rare for a building to collapse due to flooding, these elements could potentially be included in future flood risk assessments.

6. Conclusion

As climate change becomes an increasing threat, flooding occurrence and intensity is expected to grow. Flood risk assessments on the potential damages to buildings could in theory help policymakers supporting the right mitigation actions through spatial and economic information on the assets at risk.

The increase of new building data and digital representations of cities are becoming more available to the public. Flood risk assessments must evolve with this wave, finding a way to incorporate these information into different models which also account for the vertical dimension of structures as current 2D model assessments might lead to an underestimation of the damages. Other natural hazards models such as GEM provides a useful example for future development in flood risk analysis as an open-source building taxonomy could potentially lead to better estimates of the risk to assets.

Many doubts still remain surrounding flood damage estimates and more research is needed to decrease the uncertainties related to depth-damage functions and maximum damage. 3D models seems to show potential to better highlight the spatial distribution of these areas and assets of high damage values compared to a traditional 2D model.

As the world becomes more connected, and structural data more available, information on building attributes could open up opportunities for more in depth risk assessments enhancing our understanding of the relationships between the urban environment and flood hazards.

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