Semantic 3D city models as support for urban flood resilience
Experiences from Rotterdam

Andriessen, Lara; Agugiaro, Giorgio; Borgers, Aloys; Pauwels, Pieter

DOI
10.5194/isprs-annals-X-4-W4-2024-5-2024

Publication date
2024

Document Version
Final published version

Published in
International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences

Citation (APA)
Andriessen, L., Agugiaro, G., Borgers, A., & Pauwels, P. (2024). Semantic 3D city models as support for urban flood resilience: Experiences from Rotterdam. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *10*(4/W4-2024), 5-12. https://doi.org/10.5194/isprs-annals-X-4-W4-2024-5-2024

Semantic 3D city models as support for urban flood resilience: experiences from Rotterdam

Lara Andriessen[1], Giorgio Agugiaro[2], Aloys Borgers[3], Pieter Pauwels[3]

[1] BIM-Connected, Torenallee 62-22, 5617BD Eindhoven, The Netherlands – lara.andriessen@bim-connected.com
[2] 3D Geoinformation group, Delft University of Technology, Faculty of Architecture and the Built Environment, Department of Urbanism, Julianalaan 134, 2628BL Delft, The Netherlands – g.agugiaro@tudelft.nl
[3] Department of the Built Environment, Eindhoven University of Technology, PO Box 513, 5600MB Eindhoven, The Netherlands – {a.w.j.borgers, p.pauwels}@tue.nl

Keywords: Flood Resilience Score, Spatial planning, CityGML, 3DCityDB, QGIS.

Abstract

This paper presents a process to develop a CityGML-based 3D city model that, together with results from a flood simulation, can be used to investigate direct and indirect effects of floods on a city, its inhabitants and its critical infrastructure, and to quantify such effects by means of a Flood Resilience Score. In addition, the model can be used as a spatial planning support tool for urban planners to prioritise the redevelopment of certain areas and to test new spatial design decisions. First, a semantic 3D city model is prepared and enriched with additional building and infrastructure information. Then a Flood Resilience Score (FReSco) is defined and computed by quantifying the direct and indirect impacts of flooding on buildings, households, and critical infrastructure points using information from both the 3D city model and the flood simulation results. Lastly, a prototype of a spatial planning support tool is proposed to evaluate the flood resilience of a new environmental plan. As a case study, the neighbourhood of "Nieuw Kralingen" in Rotterdam was chosen. Overall, the outcomes of this work are meant to help cities better understand the impacts of flooding and adjust their urban planning activities accordingly. At the same time, the developed methodology also tests the strengths and limits of CityGML-based 3D city models in combination with openly available data and software.

1. Introduction

Urban areas are especially vulnerable to floods due to their high population and infrastructure density. Urbanisation changes the hydrological status of urban areas and the flow path of the water by building new roads and buildings, and, at the same time, destroying a city's natural flood defence system in the process (World Economic Forum, 2019). One of these natural flood defence systems is the soil's capacity to absorb the excess water. In urban areas, however, the water infiltration rate of soil is too low because of soil compaction which leads to increased instantaneous flooding (Yang and Zhang, 2011). Instead of increasing the soil's infiltration rate by incorporating more green belts, for example, cities heavily rely on their man-made sewage systems to transport the excess water outside of the city. Building flood-resilient cities is therefore becoming increasingly important to mitigate more extreme urban hazards, withstand the increased threats and recover from incidents more quickly. City planners, therefore, need a way to test how the existing built environment as well as new urban plans will hold up against floods in the future to be able to build flood-resilient cities.

It is nearly impossible to predict exactly how water will behave within a city and what kind of effect it might have without any support tools or data collection on prior flooding events. By giving city planners a spatial-design decision tool to evaluate the flood resilience of their environmental plans, they can make sure that new urban designs can live up to their full potential in contributing to the flood resilience of the city. The utilisation of urban analyses and planning tools is becoming more pressing to make well-founded spatial planning decisions. To understand and manage dynamic and complex cities, semantic 3D city models are a promising, newly emerging type of data-driven base model to conduct complex urban analyses. But while municipalities are developing their own 3D city models, they often do not fully exploit the potential of these models. At the same time, having stakeholders develop their own version of a 3D city model creates stand-alone models that are not interoperable with other 3D city models (Stoter et al., 2020). This makes scaling up nearly impossible and limits professionals in making well-informed urban decisions. Other challenges that are slowing down the adoption of semantic 3D city models are spatial decision tools. For example, there are already a variety of tools available to help end-users make use of the 'digital twin' technology, however, these tools are often not user-friendly, require a certain insight and programming skills, have a long learning curve, and most importantly, do not complement each other. Additionally, these tools are very often conceived and developed keeping just a specific user in mind, such as a city planner, a hydrologist, an asset manager, etc. Stoter et al. (2020) support this claim by stating that city planning and environmental simulations are fields where the availability and application of 3D models still have room to grow. This is why urban planners have yet to fully integrate semantic 3D city models into their workflows. This claim is also supported by this research which focuses on going through the whole process of developing a methodology to perform urban flood risk analysis using a semantic 3D city model and using open standards and open data from the point of view of an urban planner. As a matter of fact, existing flood models are currently incapable of identifying the direct and indirect effects of a flood on a city's infrastructure and its inhabitants as they are missing important information on the urban environment itself that goes beyond the geometries and infiltration rates used for standard flood simulation models. By connecting a flood model to a semantic 3D city model which is capable of representing a great amount of urban data, the flood resilience of a city could in theory be assessed.

2. Related work

Ghaith et al. (2021) tried designing a framework to "devise a city digital twin under flood hazards through the integration of data acquisition systems, hydrology and hydraulic modelling, physical infrastructures and entities, demographic information, and real-time system behaviour" using the city of Calgary, Canada as a study case. Based on this framework, digital twins should be able to imitate floods and their impact on a city's infrastructure, identify vulnerable locations in the city during a flood, increase a city's flood resilience, and develop strategies to mitigate the risk of floods. For example, the 3D city model of Antwerp can visualise the effects of floods on a city due to heavy rain over time to support decisions on where to build infrastructure that reduces or prevents flooding (Coenen et al., 2021). So far, models that include a time element are scarce which makes the model of Antwerp quite unique (so far). However, until now, the model can only run two specific scenarios and is therefore only a demo version. Figure 1 visualises a flood in the centre of Antwerp and the effect that the resulting flooding has on the traffic flow and air quality in the city during morning rush hour (8:00 AM).

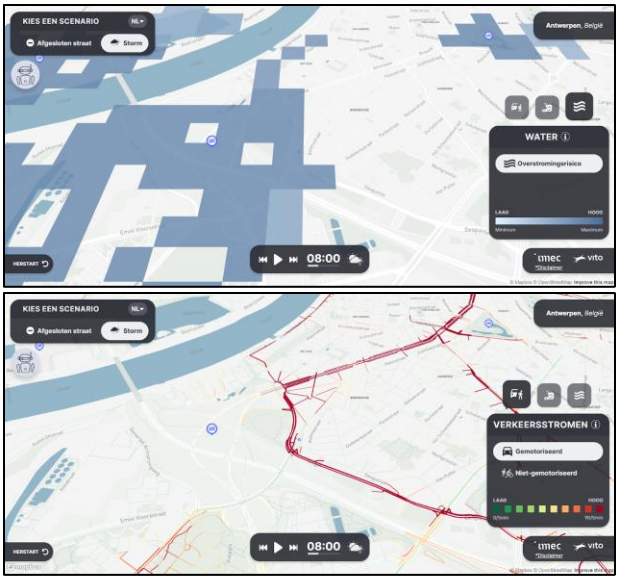

Figure 1. Digital twin demo of Antwerp showing the flood risk resulting from a storm [top] and the effect that the flood would have on the traffic flow [bottom]. Screenshots source: IMEC (2018).

Another example is the UK's web-based Climate Resilience Demonstrator (CReDo). It consists of a 2D digital twin of the UK which is meant to assess the impact of climate change (and flooding in particular) on the country's energy, water, and telecom network (National Digital Twin Programme, 2022). CReDo models the interdependencies between infrastructures to assess the effect of a flood on a city and, in the future, on a country-wide scale. To demonstrate the functionality of the digital twin without leaking sensitive infrastructure data, CReDo uses synthetic data to simulate one pre-programmed flood scenario with a handful of prescribed implementation choices and their ranked monetary costs and resilience score.

In the Netherlands, the company Movici has developed a 3D model of the Netherlands and its critical infrastructure which takes into consideration the country's road, train, electricity, gas, sewage, and telecom network as well as its air- and seaports. The interconnectedness between the infrastructures is modelled and potential scenarios of the future are simulated and visualised. Figure 2 depicts an example of the "impact" interface from the software platform SIM-CI (now known as Movici) which measures the potential cascading effects of a sluice break in the Hague.

Figure 2. User interface of the SIM-CI software platform. Screenshot source: NGInfra (n.d.).

In Germany, the city of Dresden is developing a versatile 3D city model that is used for several applications: the visualisation of traffic routes and flows, environmental analyses of noise and flood propagation, 3D views of varying urban and development plans, an overview of industrial hubs within the city, support during major events. Overall, the 3D city model is used as a publicly available representation of the city in 3D. It has also led to the development of the "3D-Starkregenportal" (3D heavy rain portal) and the "Dresden 3D Hochwasserthemen" (Dresden 3D Flood issues) tool. The former uses the 3D city model as a database to evaluate the effect of heavy rain on the built environment in three test areas. The tool provides building-specific information on flood risks, potential heavy rain damage and options for action. Figure 3 depicts the model that calculates the surface run-off resulting from a heavy rainfall of 42.1 mm of water within an hour (expected every 30 years) including the expected costs from damages in the neighbourhood of Striesen.

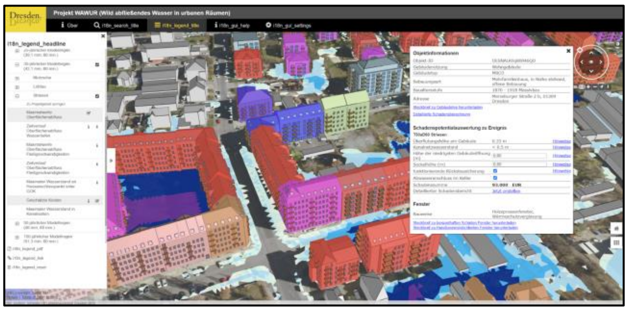

Figure 3. Example of surface runoff and expected costs from damages for buildings resulting from heavy rainfall in Dresden due to river Elbe. Screenshot source: Landeshauptstadt Dresden (2020).

3. Methodology

3.1 Overview

This paper presents a process to evaluate the flood resilience of urban areas by preparing a CityGML-based city model that can be used in connection with the results of a flood simulation model to uncover the direct and indirect effects of future floods on a city, its inhabitants and its critical infrastructure. Such effects are quantified by means of a so-called "Flood Resilience

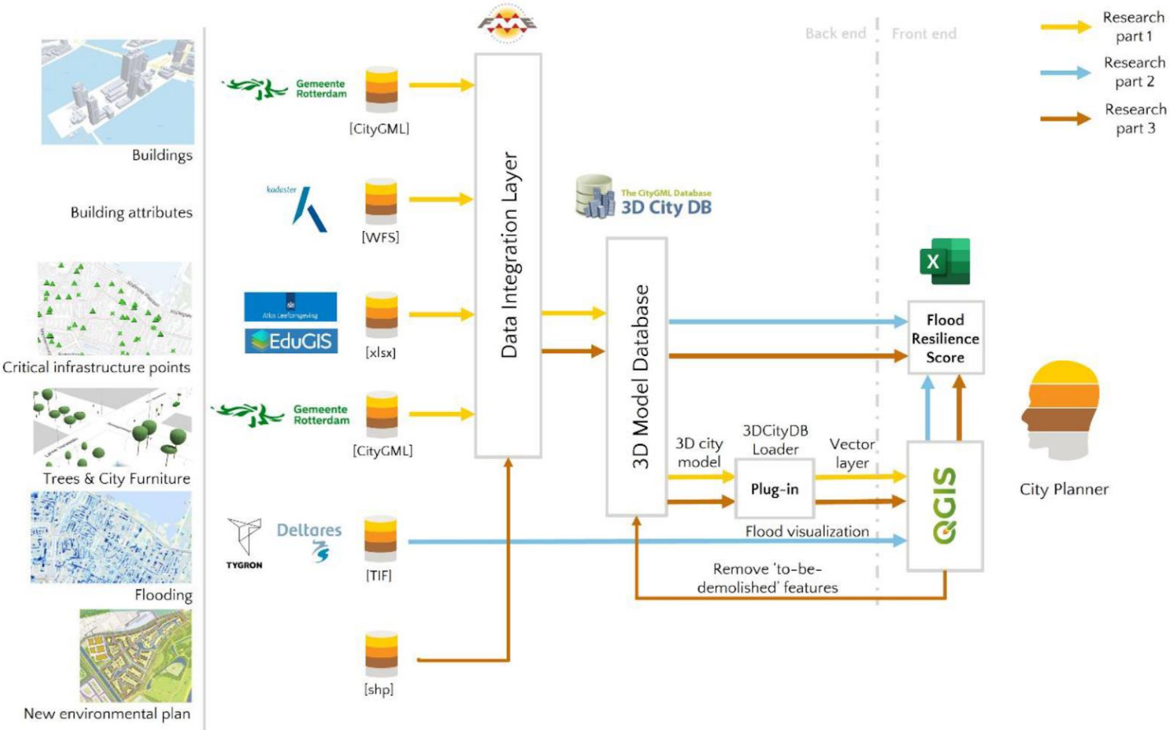

Figure 4. Overview of the process to evaluate flood resilience of an urban area using a semantic 3D city flood model and a spatial-design decision tool.

Score" (FReSco). In addition, this study explores the potential of using the developed model as a spatial planning support tool for city planners to prioritise the redevelopment of certain areas and to test new spatial design decisions with regard to flood risk. When developing the methodology, one of the main underlying questions strongly contributing to the process was: "Would urban planners be able to use this model by themselves, although with possibly some support by ICT and domain experts?" Therefore, different approaches for certain sub-tasks were initially explored and evaluated, such as the choice of which source of data, the use of which software tools, and the overall level of complexity to gather, integrate and use the required data for the computation of the Flood Resilient Score. Eventually, the resulting process consists of three parts; (1) the integration and enrichment of a semantic 3D city model with results of a flood simulation model, (2) the definition and implementation of a Flood Resilience Score, and (3) the set-up of a prototypic spatial planning support tool for urban planners. Figure 4 depicts the overview of the process.

In the first part (1, yellow arrows), spatial and non-spatial urban data needs to be obtained and integrated. Here, the decision was made to start from a CityGML-based dataset, as the standard allows to model different urban objects. If required, the buildings must then be enriched with additional attributes. If not already available, the 3D city model can be further enriched with additional city objects such as city furniture (lamp posts, trash bins), and vegetation objects (trees) in order to create a more complete 3D scene. The results from a flood simulation in the form of flood maps are then used together with the 3D city model. Data exploration and visualisation, as well as most of the next steps, are carried out in the free and open-source software QGIS.

A Flood Resilience Score is formally defined in the second part (2, blue arrows). Its main purpose is to provide a way to quantify, and therefore more easily compare the effects of flooding in different areas of the city (in the case of the same scenario) or to compare different scenarios (e.g. the status quo and a future development of an urban area). Although the computation of the Flood Resilience Score is presented in Figure 4 as the second step in the methodology, it is relevant to note here that its conceptual development is the result of an iterative process that has been influenced by working with (realistically) available data coming from the first step.

In the third and last part (3, brown arrows) the urban planner can perform the envisioned spatial analyses. Here, the interaction with the 3D city model, the flood simulation results, and the computation and visualisation of the Flood Resilience Score are enabled for different scenarios. Different future urban development scenarios can be loaded and can interact with the existing 3D city model. The starting points are 'simple' shape-files representing the georeferenced footprints of the newly planned buildings. It is relevant to clarify here that we intentionally and deliberately aimed to deliver a semi-automated and not an automated workflow. This gives urban planners and domain experts the needed opportunity to customise certain data and computational procedures. Of course, the level of automation can still be improved on-demand and in support of specific requirements and purposes.

3.2 Definition of the Flood Resilience Score

The Flood Resilience Score (FReSco) is intended to quantify the flood resilience of an urban area. The score is meant to allow urban planners to compare individual urban areas with each other, showing which current urban areas are currently at risk of flooding, or what the risk could be for future urban development areas. The main idea behind the Flood Resilience Score is not only to focus on buildings that might be flooded as well as the number of affected households living in these buildings, i.e. *directly* affected by a flood, but also to consider whether they may be *indirectly* affected. For example, a residential building may not be directly flooded, but if the nearby supermarket or hospital is flooded, then this will indeed have an impact on the people living in that building. Therefore, the Flood Resilience Score does not only consider buildings, but it includes so-called critical infrastructure points.

As the name says, critical infrastructure points are those urban features that play a critical role in how the urban infrastructure works under normal conditions. According to their relevance, they are further divided into vital (e.g. fire stations, hospitals, distribution centres, telecommunication masts, and sewage pits), vulnerable (e.g. hospitals, nursing/elderly homes, and monuments and world heritage sites) and dangerous (e.g. energy (nuclear) power plants and storages of hazardous substances) points when flooded (Rijksoverheid, 2022; Karagiannis et al, 2019). For the Flood Resilience Score, the status of 'directly' or 'indirectly' affected urban features is derived by means of GIS-based spatial overlay operations. Using the 3D city model as the source of information for the buildings and the other infrastructure points, these are overlaid to the layer(s) representing the flooded areas. Such layers are generally provided as raster-based layers resulting from domain-specific flood simulation tools. In general, each cell represents whether the specific underlying area will be flooded, and the height of the water level above the terrain corresponding to that cell. Therefore:

- *Directly* affected buildings and infrastructure points are identified and classified as such if they lie partially or completely within a flooded cell (or group of cells). A spatial overlay is then carried out between their 2D representations (a point or a polygon representing their footprint) and the layer containing the flood results.
- For *indirectly* affected buildings, a buffer-based approach is chosen to determine whether a feature is affected or not. Taking a supermarket as an example, if it is flooded, then all buildings within a certain radius will be classified as indirectly affected, as they may not be able to access the supermarket anymore due to the flood. The buffer size can vary and can be set by the user. Alternatively, values from regulations can be used. For example, in the case of the Netherlands, a supermarket is generally available within a 500-meter distance from any building (Compendium voor de Leefomgeving, 2022). Here, the limitation of the buffer-based approach is that there may be other non-flooded supermarkets within the buffer zone that residents can divert to.

As such, each building and critical infrastructure point is assigned a label ('flooded', 'affected by flood', 'within reach of dangerous infrastructure point') to represent their status in the event of a flood. Using this approach, it is then possible to quantify the following parameters within the study area and the immediate surroundings, which are then used to compute different Flood Resilience Scores.

- Number of all buildings (N_{bdg}):
  - Number of directly affected buildings (N_{d_bgd})
  - Number of indirectly affected buildings (N_{i_bgd})
- Number of all households (N_{hh}):
  - Number of directly affected households (N_{d_hh})
  - Number of indirectly affected households (N_{i_hh})

All Flood Resilience Scores refer to the same selected study area a, for a flood event f, and are expressed between 0% (i.e. the study area has no flood resilience at all) and 100% (i.e. maximum flood resilience). Two classes of FReScos, each one further specialised in two subclasses, have been defined and are computed as follows.

The first class contains "asset-driven Flood Resilience Scores" and is composed of:

1) FReSco based on directly affected buildings:

$$FReSco_{a,f,d\_bdg} = \left(1 - \frac{N_{d\_bdg}}{N_{bdg}}\right) \cdot 100 \qquad (1)$$

2) FReSco based on both directly and indirectly affected buildings:

$$FReSco_{a,f,di\_bdg} = \left(1 - \frac{N_{d\_bdg}+N_{i\_bdg}}{N_{bdg}}\right) \cdot 100 \qquad (2)$$

The second class contains "residence-centric Flood Resilience Scores" and is composed of:

3) FReSco based on directly affected households:

$$FReSco_{a,f,d\_hh} = \left(1 - \frac{N_{d\_hh}}{N_{hh}}\right) \cdot 100 \qquad (3)$$

4) FReSco based on both directly and indirectly affected households:

$$FReSco_{a,f,di\_hh} = \left(1 - \frac{N_{d\_hh}+N_{i\_hh}}{N_{hh}}\right) \cdot 100 \qquad (4)$$

The resulting FReSco scores can then be used to compare different areas in the same city at the same time, or, as in this case, to evaluate whether a new urban development scenario in a certain area positively or negatively affects the overall flood resilience.

4. Implementation

4.1 Study area

An area located in the north of the Dutch city of Rotterdam was identified, as it is the place of a planned construction of a new neighbourhood, called "Nieuw Kralingen". The selection of the study area is the result of a preliminary analysis carried out to check the availability of the required data. A map indicating the location of the study area in Rotterdam is provided in Figure 5. The municipality of Rotterdam has developed a 3D city model for the whole city, called "Rotterdam 3D" (Gemeente Rotterdam, n.d.) which is available to the public and allows any user to either simply explore the 3D city model online or to download sections of the model in different formats such as, among others, CityGML. The available 3D city model contains geometries of buildings, trees, and some city furniture, such as street lanterns, bicycle racks, and parking meters.

Figure 5. Position of the study area in Rotterdam with the approximate extents of the "Nieuw Kralingen" neighbourhood highlighted in red. Basemap data from OpenStreetMap.

Nevertheless, additional datasets were collected to be later integrated with the 3D city model or to enrich it in terms of available attributes. These additional datasets contain information about the city's infrastructure network including critical infrastructure points and the number of households for each building. For the former, Atlas Leefomgeving (n.d.), eduGIS (n.d.), and Google Maps were used, while for the latter, the Dutch BAG dataset ('Basisregistratie Adressen en Gebouwen', i.e. Addresses and building registration) was used. In particular, the Atlas Leefomgeving and eduGIS provide geographic information on the location of buildings and their specific function that can be classified as vital, vulnerable, or dangerous, while the BAG dataset contains the addresses of buildings, as well as additional information such as the year of construction, the broader building function, etc. Finally, the simplified flood simulation model 'Rainfall Overlay', originally developed by the company software developer Tygron (n.d.), was chosen for this research as the simulation results in the form of a static flood inundation map are freely accessible through the Klimaateffectatlas (n.d.). The flood simulation model simulates a rainfall of 2 hours followed by a dry period of 4 hours. During the 6 hours, the maximum inundation depth is recorded for each 2x2m raster cell (Deltares, 2018). Figure 6 provides examples of the raster-based flood simulation results. On the left, the maximum inundation level is shown for the first simulated rainfall intensity, on the right, the results of the second one.

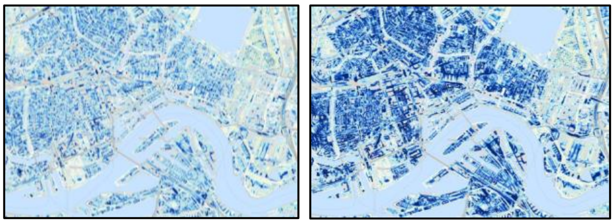

Figure 6. Excerpt of the flood inundation map of Rotterdam resulting from a rainfall intensity of 70mm (left) and 140mm (right) during 2 hours. Screenshots source: Klimaateffectatlas (n.d.)

4.2 Data preparation

A series of data integration operations were carried out mainly in Safe Software's FME. First, the list of critical infrastructure points was obtained by integrating existing information from the existing sources and manually enriching it with additional entries taken by means of visual inspection in Google Maps. Regarding the 3D city model, the datasets containing building information were used to enrich the buildings with the following attributes which was done by editing the CityGML files and adding additional properties to selected elements:

- their BAG ID,
- their function(s),
- their address(es),
- the neighbourhoods they are located in,
- the number of households in each building.

Additionally, buildings and other city objects that were identified as critical infrastructure points were further characterised when it comes to their class (vital, vulnerable, and dangerous). Eventually, the CityGML files of the 3D city model were imported into an instance of the 3D City Database (Yao et al., 2018). In between, visual inspections of the datasets during the data integration process were carried out using either the KIT's FZK Viewer or Safe Software's FME Data Inspector.

When it comes to the future development of the study area in "Nieuw Kralingen", the urban plans for the new neighbourhood were collected. Unfortunately, these plans are only available in jpg format from the project's website (Nieuw Kralingen, n.d.), as neither 2D nor 3D vector-based data can be retrieved from open data sources. Still, in order to overcome such hindrance, and given the relatively limited size of the new development area, a shape-file was first created by manually digitising the 584 building footprints available in the jpeg image. During the process, each building footprint was assigned a unique ID, conceptually comparable to the BAG ID of the buildings in the 3D city model. Successively, the 2D footprints were transformed into 3D buildings. For the footprint height, the national DTM was used. Due to the lack of more detailed geometrical information, a standard extrusion height of 10m was used, eventually generating CityGML-based LoD1 building models. In terms of attributes, the same ones as with real buildings were used, however with the following simplifications: all new buildings are residential and contain globally 800 households distributed equally over the number of buildings. Finally, no critical infrastructure points were defined within the new development area. The whole process was carried out by means of an FME workbench procedure specifically created for this purpose. Figure 7 [left] provides an overview of the "Nieuw Kralingen" new development plan, with the digitised building footprints represented in orange, while Figure 7 [right] shows the 3D model of the planned new buildings. The whole data preparation process turned out to be rather time-consuming despite the availability of data in most common standard formats. From the point of view of the city planner this step resulted in more manual work than expected.

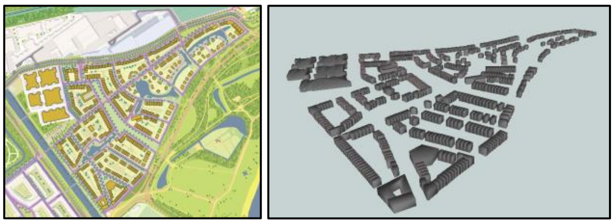

Figure 7. [Left] In orange, the manually digitized building footprints, shown on top of the georeferenced "Nieuw Kralingen" plan. Image adapted by the authors and originally from: architectuur MAKEN (n.d.). [Right] Resulting 3D model of "Nieuw Kralingen" visualised in FME Data Inspector.

4.3 Computation of the Flood Resilience Score

Once the datasets were collected and prepared as described in the previous sections, QGIS was chosen as the GIS environment in which to carry out the following operations aiming to compute and analyse the Flood Resilience Scores (FReScos). The decision to use QGIS is due to several reasons. First, it is a free and open-source software that is sufficiently widely known and used, also by the intended target final users: urban planners needing to evaluate the flood resilience of an urban area. Second, it allows performing the required analysis and visualising the results, in 2D and 3D, thanks to the already available GIS analysis tools. Finally, its out-of-the-box functionalities can be further extended by several plug-ins. Of particular relevance for this work are the '3DCityDB-Tools' and the 'Qgis2threejs' plug-ins. The 3DCityDB-Tools plug-in (Agugiaro et al., 2024) allows to connect to local or remote instances of the 3DCityDB and to load data as 'classical' layers into QGIS, de facto hiding the complexity structure of the underlying database schema. Once data 'layers' are available in QGIS, the user can interact with them as usual, i.e. perform analyses, work with associated attributes, explore and visualise the data in 2D and 3D, etc. Additionally, the 3DCityDB-Tools plug-in allows users to easily edit attributes of the CityGML city objects. The Qgis2threejs plug-in can visualise DEM and vector data in 3D on web browsers. In QGIS itself, it also represents a valid alternative to QGIS' 3D Map viewer. Examples of data exploration and visualisation, in 2D and 3D, are presented in Figure 8.

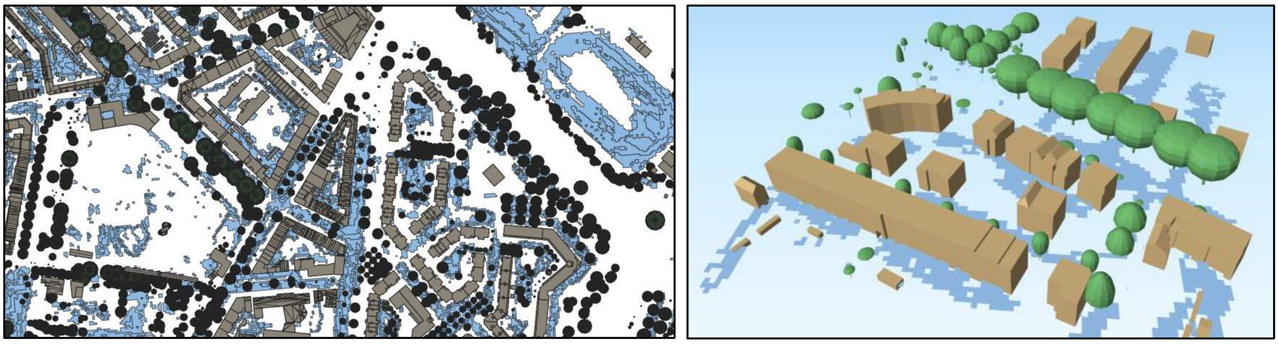

Figure 8. Examples of visualisation in QGIS of the 3D city model data and flood simulation results in 2D [left] and 3D [right] using the 3DCityDB-Tools and the Qgis2threejs plug-ins.

Figure 9. [Left] Example of buildings directly (in orange) or indirectly (in red) affected by the flood. [Right] Example of vulnerable infrastructure points (in violet) directly affected by the flood. Basemap data from OpenStreetMap.

Overlay operations using the layers containing vector data from the 3D city model and the raster-based results of the flood simulations, as well as the creation of buffers (of 500m), whenever required, were carried out using the standard QGIS operations. In this way, the number of buildings and households (both directly and indirectly affected), as well as the number of affected infrastructure points can be computed as explained in Section 2.2. Figure 9 [left] presents an excerpt of the study area where directly affected buildings (i.e. actually flooded) are represented in orange, while indirectly affected buildings are represented in red. Figure 9 [right] presents instead an example of vulnerable infrastructure points (in violet) that are directly affected by the flood. Eventually, the Flood Resilience Score was computed. Figure 10 shows an example of different Flood Resilience Scores per neighbourhood giving an indication of which neighbourhoods score well and which do not. The results also show that several neighbourhoods are indirectly affected by a flood whereas other neighbourhoods are not. Furthermore, Figure 11 [left] shows the comparison of the FReSco scores conserving two different rainfall scenarios over the study area. While the rainfall intensity has doubled, the flood resilience of the study area has decreased by 10%.

4.4 Flood Resilience Score for scenarios

With the overall procedure ready to compute the Flood Resilience Score in a study area for the current situation (status quo), the next and final step consisted of performing the same operation with the future development scenario in “Nieuw Kralingen”. This scenario was used to test, on the one hand, the overall usability of the so-far developed prototype, and, on the other hand, to evaluate the flood resilience of these new plans.

A copy of the current 3D city model was loaded in a second instance of the 3DCityDB. Then, using the 3DCityDB-Tools plug-in, the current existing buildings inside the study area were ‘digitally demolished’ (i.e. deleted) and the new 3D buildings were loaded and added to the new 3D city model, creating a ‘new’ city model representing the future urban configuration, but having the exact same characteristics and data structure of the present one. While it is possible to manually delete and recreate a part of the digital city model using CityGML and 3DCityDB, this is much more complicated for the flood simulation results. In principle, an entirely new flood simulation needs to be executed, using the new city model, leading to a new flood simulation. These new flood simulation results can then be added to the revised city geometry. This is not implemented in the current procedure, and only the initially obtained flood simulation results are used. Currently, this is one of the greatest limitations of this research. Nevertheless, despite using the current flood simulation results instead of the future ones, a new FReSco score was computed and compared with the one of the current situation (i.e. ‘status quo’). This can in any case give us an indication whether the software prototype and computational procedures are technically and conceptually feasible. Figure 11 [right] provides a representation of the new FReSco scores for the future development scenario. While taking the limitations of the flood inundation map into consideration, it can be seen that the FReScos of Nieuw Kralingen are better than the average neighbourhoods within the total study area even though the “Kralingse Plas” and the “Berge Voorplas”, two large bodies of water, are located right next to “Nieuw Kralingen”. The neighbourhood also scores highly on non-flooded critical infrastructure points. This, however, is caused by the absence of critical infrastructure points within the area. Nevertheless, the results can contribute to giving urban planners and municipalities insight into the flood resilience of the new environmental plans.

5. Conclusions

In the face of increasing climate-related risks, there is a pressing need for proactive flood-resilient city planning. The work presented in this paper adopts a CityGML-based semantic 3D city flood model to assess the flood resilience of urban areas and it can be used to complement and support spatial planning opera-

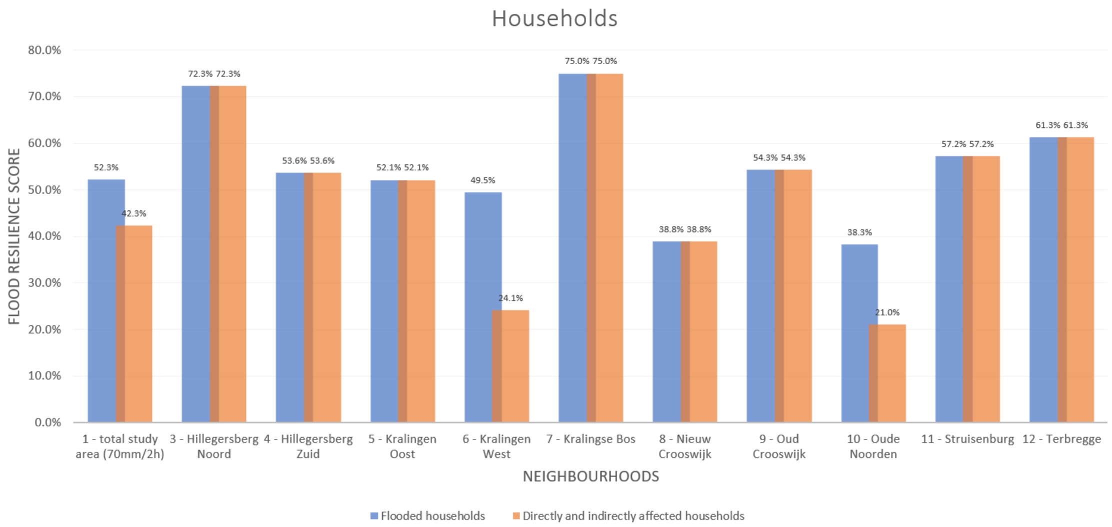

Figure 10. Bar diagram of Flood Resilience Scores for households in different neighbourhoods in and around the study area

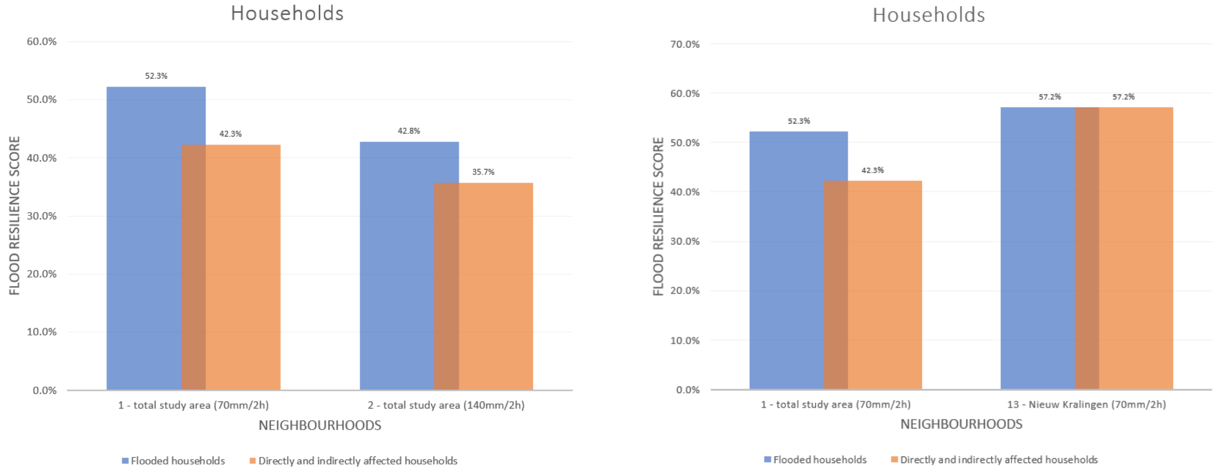

Figure 11. [Left] Bar diagram of Flood Resilience Scores for households using two rainfall intensities. [Right] Bar diagram of Flood Resilience Scores for households for the status quo scenario (i.e. today) and for "Nieuw Kralingen" after its construction.

tions. All steps encompassing data collection, enrichment, and tool development, have been described and enable users to compute Flood Resilience Scores (FreSCo) for different areas and scenarios, facilitating effective comparisons.

The primary objective of this work is to assess the direct and indirect impacts of future floods on a city, its residents, and critical infrastructure, ultimately quantifying these effects through a Flood Resilience Score. Additionally, the paper explores the utility of the developed model as a spatial planning support tool for city planners to prioritise redevelopment areas and test new spatial design decisions, using a neighbourhood of the city of Rotterdam as a case study. One of the ideas behind the development of the presented methodology has been to simplify - as far as reasonable - the access to the used technologies and tools so that urban planners would be able to use them. Although some hurdles and limitations still exist, and further refinements are planned, the resulting prototype already represents a positive step toward better usability for non-experts.

However, it is important to highlight here some limitations, as they influence the reach and relevance of the findings on urban flood resilience through 3D city models and flood analyses. One of the bigger limitations of this work resides in the use of flood simulation results of the status quo scenario also for future scenarios. Hence, the flood simulation for future scenarios is incorrect. In the extent of this work, it was not possible to include a live connection to the needed flood simulation tool, and therefore it was not possible to redo the simulation interactively. Just replacing them with the correct simulation results would be feasible (provided the data is available), but a major improvement should consider a tighter coupling of the 3D city model with the simulation tool. Another source of inaccuracy, at least in the study area of "Nieuw Kralingen", is the lack of any critical infrastructure points for the future development scenario, as this information is not available at the moment, and this therefore leads to more favourable results compared to the status quo scenario. At the same time, critical infrastructure points outside of the study area were not taken into account even though they might have an impact (e.g. there is no hospital within the study area, however, if the nearest hospital gets flooded, inhabitants within the study area will still be affected). This limitation can be traced back to the high data dependency of the study.

Looking at a possible future improvement, a tighter integration with subterranean (building) data, (underground) utility networks and emergency response simulations would enhance the research's depth and applicability, providing a more holistic perspective on urban resilience. Additionally, it might be interesting to test and reproduce results in different cities of (at least) the Netherlands. Speaking of further possible improvements, automation is an aspect from which the proposed methodology and the developed prototype could greatly benefit. This refers to both the initial step of data collection and integration, and to the successive usage of the data. On one hand, the first step briefly described in this paper (but in reality rather complex and time-consuming) should be drastically reduced if such a 3D city flood model were already available. On the other hand, when it comes to "using" a 3D city model, software operations should be somehow streamlined, either via APIs or, as an alternative, via user-friendly interfaces that extend well-known existing tools such as QGIS. This way, urban planners could more easily interact with the 3D city model, the simulation results, and compute/compare the Flood Resilience Score. More details can be found in Andriessen (2023).

A final comment is on the role of semantic 3D city models as tools to support the understanding and management of complex urban systems, at least from the point of view of the urban planning domain experts. These models, while increasingly adopted for various applications, still face some challenges before their full potential can be exploited. As directly experienced during nearly all steps related to the work presented in this paper, the lack of standardised, user-friendly tools and interoperability issues between 3D city models and other tools may still pose as barriers, potentially discouraging city planners from using such tools. Nevertheless, things are slowly changing – the 3DCityDB-Tools plugin for QGIS is a good example in this direction – and this paper has tried to demonstrate this, while still advocating for further automation and user-friendly interfaces.

Acknowlegements

OpenStreetMap data (© OpenStreetMap contributors, License: www.openstreetmap.org/copyright) have been used in QGIS as basemap to create some of the figures contained in this paper.

References

Agugiaro, G., Pantelios, K., León-Sánchez, C., Yao, Z., Nagel, C., 2024. Introducing the 3DCityDB-Tools plug-in for QGIS. *Recent Advances in 3D Geoinformation Science* – Proceedings of the 18th 3D GeoInfo Conference, Springer.

Andriessen, L.C.M, 2023, Building flood resilient cities : Developing a semantic 3D-city flood model for spatial planning support with a Flood Resilience Score.
Eindhoven University of Technology, MSc thesis. https://research.tue.nl/nl/studentTheses/building-flood-resilient-cities (31 January 2024)

Architectuur MAKEN, n.d., Nieuw Kralingen, https://architectuurmaken.nl/projecten/nieuw-kralingen-2/ (31 January 2024)

Atlas Leefomgeving, n.d. https://www.atlasleefomgeving.nl/kaarten (31 January 2024)

Coenen, T., Walravens, N., Vannieuwenhuyze, J., Lefever, S., Michiels, P., Otjacques, B., Degreef, G., 2021. Open Urban Digital Twins - insights in the current state of play. White paper. Version 1.1. Interuniversitair Micro-Electronica Centrum

Compendium voor de Leefomgeving, 2022. Nabijheid levensmiddelenwinkels en bibliotheken, 2008-2020. https://www.clo.nl/indicatoren/nl2197-afstand-tot-voorzieningen (31 January 2024)

Deltares, 2018. Overstromingsrisico's door intense neerslag. Ministerie van Infrastructuur en Waterstaat. https://klimaatadaptatienederland.nl/publish/pages/153817/rapportage_-_overstromingsrisicos_door_intense_neerslag.pdf

EduGIS, n.d. https://kaart.edugis.nl (31 January 2024)

Gemeente Rotterdam, n.d. Rotterdam 3D. https://www.3drotterdam.nl (31 January 2024)

Ghaith, M., Yosri, A., El-Dakhakhni, W., 2021. Digital twin: A city-scale flood imitation framework. In CSCE 2021: Canadian Society for Civil Society for Civil Engineers Annual Conference, 577-588.

IMEC, 2018. IMEC Urban Digital Twin of Antwerp. https://digitaltwin.imec.be (31 January 2024)

Karagiannis, G.M., Turksezer, Z.I., Alfieri, L., Feyen, L., Krausmann, E., 2019. Climate change and critical infrastructure - floods. Publications Office of the European Union.

Klimaateffectatlas (n.d.). https://www.klimaateffectatlas.nl/nl/ (31 January 2024)

Landeshauptstadt Dresden, (n.d.). Project WAWUR (Wild abfliessendes Wasser in urbanen Räumen). https://wawur.virtualcitymap.de/#/ (31 January 2024)

National Digital Twin Programme, 2022. CReDo: An overview. Digital Twin Hub. https://digitaltwinhub.co.uk/files/file/142-credo-an-overview/ (31 January 2024)

NGinfra, n.d. MOVICI: Modelling and visualizing critical infrastructures. https://www.nginfra.nl/movici/ (31 January 2024)

Nieuw Kralingen, n.d. Wonen in Nieuw Kralingen. https://nieuwkralingen.nl/project-nieuw-kralingen/ (31 January 2024)

Rijksoverheid, 2022. Delta Programme 2023. Speed up, connect and reconstruct. Ministry of Infrastructure and Water Management; Ministry of Agriculture, Nature and Food Quality; Ministry of the Interior and Kingdom Relations. https://english.deltaprogramma.nl/documents/publications/2022/09/20/delta-programme-2023-english---print-version (31 January 2024)

Stoter, J. E., Arroyo Ohori, G.A.K., Dukai, B., Labetski, A., Kavisha, K., Vitalis, S., Ledoux, H., 2020. State of the art in 3D city modelling: Six challenges facing 3D data as a platform. GIM International: the Worldwide Magazine for Geomatics, 34.

Tygron, n.d. https://www.tygron.com (31 January 2024)

World Economic Forum, 2019. The Global Risks Report 2019. Insight Report. 14th Edition. https://www3.weforum.org/docs/WEF_Global_Risks_Report_2019.pdf

Yang, J.-L., Zhang, G.-L., 2011. Water infiltration in urban soil and its effects on the quantity and quality of runoff. *Journal of Soils and Sediments*, 11(5), 751-761.

Yao, Z., Nagel, C., Kunde, F., Hudra, G., Willkomm, P., Donaubauer, A., Adolphi, T., Kolbe, T. H., 2018. 3DCityDB - A 3D geodatabase solution for the management, analysis, and visualization of semantic 3D city models based on CityGML. *Open Geospatial Data, Software and Standards*, 3(5), 1-26.