A Coupled CA Urban Development Model (UDM) and Urban Fabric Generator (UFG) for the Assessment of Climate Hazards on Future Urban Development

Stuart Barr, Alistair Ford, Vassilis Glenis, Craig Robson, Olivia Butters and James Virgo

School of Engineering, Newcastle University, Newcastle upon Tyne, NE1 7RU, UK. (stuart.barr, alistair.ford, vassilis.glenis, craig.robson1, olivia.butters, james.virgo)@ncl.ac.uk

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Abstract

Cellular Automata (CA) spatial models have become a de facto means by which to simulate future scenarios of land use activity, particularly urban development. Increasingly, such models are being employed within large scale climate impact, adaption and resilience studies to provide future scenarios of land use change and urban development, facilitating the calculation of the economic impact of future climate hazards and development land use adaption options. However, many spatial CA models only provide information on whether land has undergone a transition from one use/activity to a new one. In the case of urban development, they are unable to provide information on the spatial pattern of new development at an intra-cell level of spatial fidelity. However, in many cases such information is important as the spatial impacts of hazards and the adaption and resilience of new urban development will be dependent on the precise spatial configuration of buildings, roads and urban green space. In this paper an Urban Fabric Generator (UFG) is presented that takes the outputs of an Urban Development Model (UDM) and simulates plausible spatial configurations of buildings, roads and urban green space. The utility of the UFG is demonstrated via two flooding case studies, where generated spatial patterns of urban form are used to parameterise a hydrodynamic pluvial flood model that evaluates the impact of future climate driven rainfall on property damage and the utility of infrastructure investment with regards to improving surface water flood resilience.

1. Introduction

Over the past two decades there has been a drive globally towards the design and development of resilient cities in order to address the increasing frequency of climate induced extreme events (Dawson, 2007; Hunt and Watkiss, 2011). With many cities situated within high-risk areas (e.g., coastal zones and within high-risk flood plains) (McGranahan et al, 2007) it is essential to understand how future urbanisation will exacerbate future risk and vulnerability of cities to extreme weather events (IPCC, 2013). As a result, many national and local governments are considering the adaptation options for their cities with regards to future urban development in order to improve their future resilience (Biesbroek et al, 2010; Carter, 2011; Reckien et al, 2014). A number of previous studies have investigated the impact of future extreme climate events on cities. For example, methodologies have been developed to assess the economic impact of future flooding (Aerts et al, 2013), human mortality from increased heat wave frequency (Hajat et al, 2014) and the resilience of urban infrastructure to natural disasters (Chang et al, 2014).

However, while such approaches are useful to demonstrate the impacts of future climate hazards, they are rarely conducted in a spatially explicit manner where hazard impacts are mapped/reported in detail for individual regions, cities or neighbourhoods (Ford et al, 2019). In studies that that have undertaken spatially explicit climate hazard impact assessments of cities, significant effort has been put into the development of methods that are able to represent the spatial pattern of future climate (via projections) and the subsequent extreme events that manifest as a result of a changing climate (Kilsby et al, 2007; Feyissa et al, 2018). However, future extreme hazard events are often integrated within risk assessments based on the current day population and urban spatial form, and fail to account for the changes in vulnerability, adaptive capacity and exposure that will result from future urban development (Ford et al, 2019).

Spatial simulation models offer one means by which the impacts of future climate hazards can be assessed on the basis of plausible future population changes and urban development (Cultice et al, 2023). National and regional spatial interaction models and land use-transport models (Ford et al, 2018, Lopane et al, 2023) have been used to investigate future population vulnerability and exposure to climate hazards such as flooding and heat (Ford et al, 2018). Microsimulation (Lomax et al, 2022) and spatial Agent-Based Models (ABMs) have been used to investigate both climate mitigation and adaption (Entwisle et al, 2016), while Cellular Automata (CA) models have been used to understand where and how land use and urban development will occur in the future and how this changes the risk from climate hazards (Wang et al, 2021). Moreover, the importance of being able to understand how population change in the future will affect the physical development has resulted in several attempts to develop ‘integrated’ multi-scale modelling systems; systems that couple spatially explicit models of population, employment, transport accessibility and urban development into a single workflow to allow climate impact assessment across multiple spatial scales and dimensions (e.g., population and urban development) (Ford et al, 2019).

However, while CA models can simulate future land use change and urban development, they do so at a relatively coarse level of detail, often only reporting where land use change or urban development is predicted to take place (Garcia et al, 2012). They rarely represent the underlying spatial pattern and configuration of new development, such as the spatial location of individual buildings, roads, urban green space within the cells recognised for development (Chen and Feng, 2022). Such information is important in situations where the actual physical form of new development is important to the magnitude of risk resulting from future climate impacts. For example, where the size, height and spatial configuration of future buildings may fundamentally change the assessed risk and/or damage resulting from an extreme event. In this paper we introduce an Urban Fabric Generator (UFG) that can be coupled to a CA Urban

Development Model such that plausible downscaled urban configurations of new development (e.g., buildings, roads and urban green space) can be generated that form a further spatial scale of analysis within the Urban Integrated Assessment Framework (UIAF) of Ford et al (2019).

2. Methods

2.1 The Urban Development Model (UDM)

The Urban Development Model (UDM) is a hybrid spatial Multi-Criteria Evaluation (MCE) (Carver, 1991; Malczewski, 2006) and Cellular Automata model (CA) (Couclelis, 1985; Cecchini, 1996; Clarke *et al.*, 1998; Wu and Webster, 1998; Engelen *et al.*, 1999; Li and Yeh, 2000; Al-kheder et al., 2008; Liu, 2008, White et al., 2012). UDM requires the predicted population P_j for each of the N zones that comprise a city or region. On the basis of a set of R spatial attractors used to predict population P and a further set of attractors R^{suit} that characterise 'local' influences on the spatial pattern of housing development (e.g., information on the performance of local schools, local accessibility (distance) to shops, services or transport hubs) UDM utilises a set of attractors R^{+} $(R + R^{suit})$ to derive a suitability surface S that indicates the suitability of any location for urban development. In UDM Linear Weighted MCE (Carver, 1991; Eastman, 1999; Malczewski, 2004) is used to derive the corresponding weights, W_i, for each attractor in R^{+} and to generate the final suitability surface S. In addition to a suitability surface, UDM also requires two further input grids; first an input constraint grid Con that indicates land that cannot be developed, and second, a grid representing the land available for development in each zone L_j^a (by default set to be $\neg Con$).

The suitability surface is used in the UDM's CA module to simulate development on the basis of satisfying the total area of land to be developed in each zone $L_j^d = \Delta P_j / P_j^p$, where ΔP_j is the magnitude of population change $(P_j - P_j^{base})$ and P_j^{ρ} is the current population density or the desired population density per zone. CA development is seeded in each zone by calculating and then ranking the mean suitability score for each parcel $S_j^{\bar{x}}$ using S. Zones are then processed on the basis of descending $S_j^{\bar{x}}$. For a parcel of land to be developed the initial development cell is derived by calculating S_j^{max} (the maximum suitability score of any cell in the parcel j). Thereafter, development is undertaken by ranking the suitability values of cells within the neighbourhood S^{Ω} of the current cell and assigning the highest ranked (highest suitability) cell to be the next cell developed. Figure 1 shows schematically the process by which an individual parcel within a zone is developed within UDM. This process is continued iteratively until the accumulator $adev$ satisfies the amount of land required for development. If $adev$ does not reach the amount of land to be developed in the zone, the next highest mean ranked parcel is chosen and the same CA development procedure initiated. This process is continued until $adev$ equals the total amount of land to be developed or if all land available for development is assigned, the difference (shortfall) in land available for development to satisfy the population is recorded. Further details on the implementation of UDM can be found in Ford et al (2019).

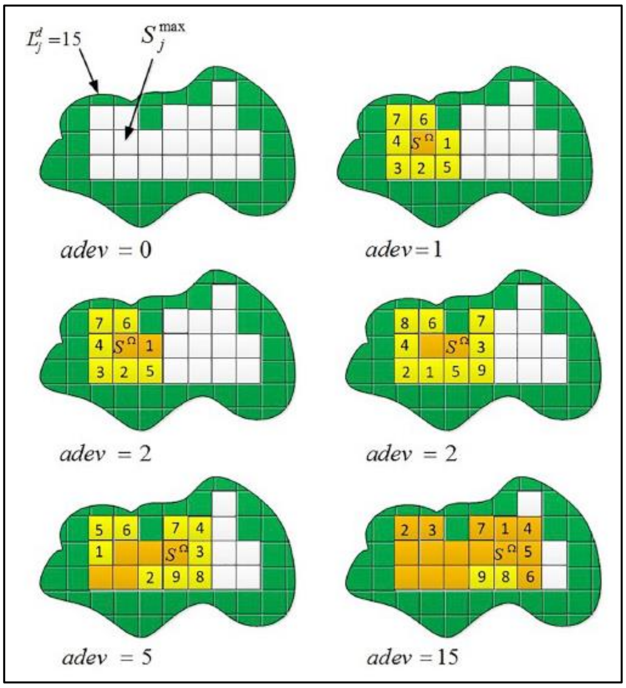

Figure 1. Schematic representation of the CA urban development procedure utilised in UDM to develop a parcel of land within a zone.

2.2 The Urban Fabric Generator (UFG)

The Urban Fabric Generator takes as its input the spatial pattern of new developed land generated by the UDM CA model and uses this to generate downscaled spatial layouts of buildings, roads and urban green space. It achieves this by using the density of development (number of dwellings per-hectare) that will be required for each developed cell within the UDM output.

In order understand the type and mix of dwellings that would be expected (in the UK) for a developed cell within the UDM output for a particular dwelling density, UFG uses the empirical results generated by Hargreaves (2015) and Hargreaves (2021). In this work, an analysis of the English Housing Condition Survey was undertaken to convert residential densities into 1-hectare tiles representing the typical spatial layout of different types of residential building stock (e.g., detached, semi-detached, terrace and flats) (Hargreaves, 2015; Hargreaves, 2021). Moreover, in Hargreaves (2015) typical residential building type mix for the number of dwellings per-hectare was also generated (Figure 2).

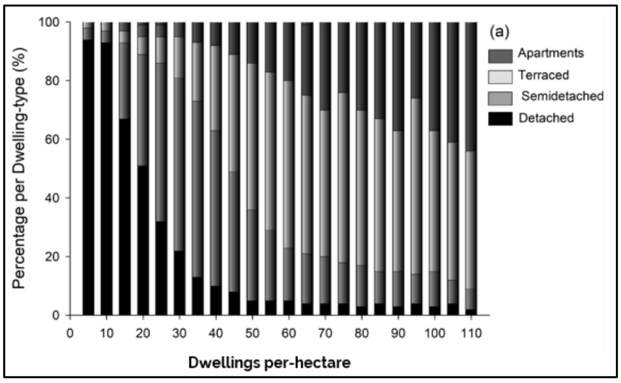

Figure 2. Percentage of dwellings per-dwelling type for a 'typical' hectare of development in England (Source: Hargreaves, 2021).

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In the UFG a procedural residential dwelling title generator generates ‘synthetic’ 1-hectare titles representing the spatial pattern of different dwelling types on the basis of the upper and lower distribution of values of dwelling-type per-hectare found in Hargreaves (2021). Figure 3 shows the results of this process for 4 1-hectares tiles of terrace, detached, semi-detached and flats; where the proportion of land occupied by buildings, road and urban green space agrees with the values reported by Hargreaves (2015) for the different number of dwellings of each dwelling type within 1-hactare.

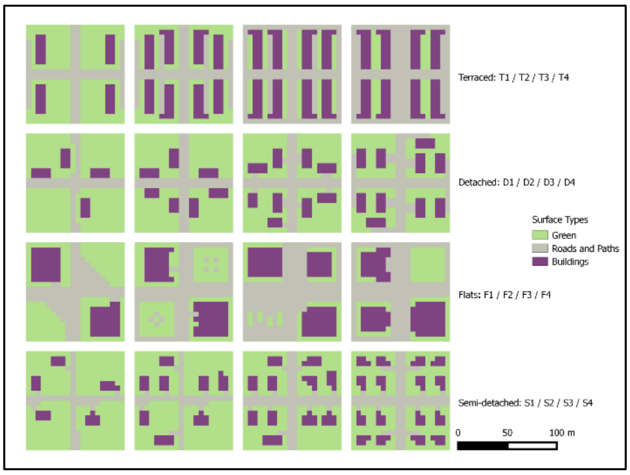

Figure 3. Urban Fabric Generator 1-hectare generated dwelling titles for different densities of dwelling-type per-hectare following Hargreaves (2021).

The assignment of particular dwelling tiles to the parcels assigned development in UDM is achieved by using the average dwelling density per-hectare of each parcel. This average dwelling density is then used to select the UFG titles required to generate an urban fabric that satisfies the required number of dwellings per-hectare. For example, if UDM assigned a parcel to be developed that had an average density of 30 dwellings per-hectare, then the UFG would look to generate an urban fabric that consisted of 20% detached housing, 60% semi-detached, 15% terrace and 5% apartments/flats (Figure 2). The result would be an urban fabric covering the entire parcel (sub-divided into 1-hacater cells) that was a tessellation of tiles that corresponds to these dwelling type values (Figure 4). In the UFG, the selection of the initial 1-heacare cell is performed randomly, as is the selection of subsequent cells and the dwelling type tile assigned.

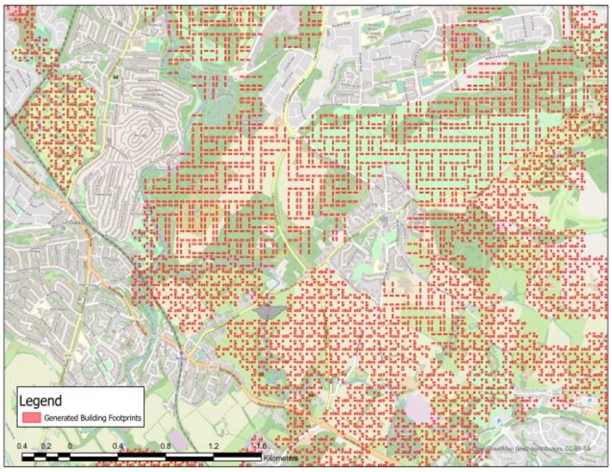

Figure 4. UFG output for a large new residential development of mixed-density mixed-type dwellings.

3. Urban Fabric Generator Case Studies

3.1 National Scale UDM Runs

As noted the Urban fabric Generator (UFG) requires as input a spatial grid that represents the land that is to be developed. It also requires for each developed area of land (cell) information on the development density (number of dwellings per-hectare). As part of the UK OPENCLIM project (Open Climate Impacts Modelling Framework; UK Climate Resilience Programme (2024)) the UDM model was used to generate for the geographic area of Great Britain (Scotland, England and Wales) future urban development for 2080; UDM results that were used in the two case studies presented in this paper.

Population projections generated by the UK Socioeconomic Scenarios for Climate Research and Policy project (SSPs) (Pedde et al, 2021, Merkle et al, 2023) were used to parametrise the national scale UDM run. The SSPs comprise of five socio-economic ‘pathways’ that represent different future population and economic outcomes for the United Kingdom relating to different socio-economic approaches to climate mitigation and adaption. In the case of this work SSP4, known as the ‘Inequality’ scenario, was employed. In SSP4 adaption dominates with economic prosperity being driven by a greening of the energy sector but at the expense of an increasing divide between wealthy and poor regions of the UK. Attractors and corresponding MCE weights for the national scale SSP4 run of UDM were carefully selected to be commensurate with the socio-economic drivers of the SSP4 scenario. Figure 5 shows the final national suitability surface used in UDM, while Figure 6 shows the resulting urban development for Great Britain in 2080 generated by UDM based on SSP4.

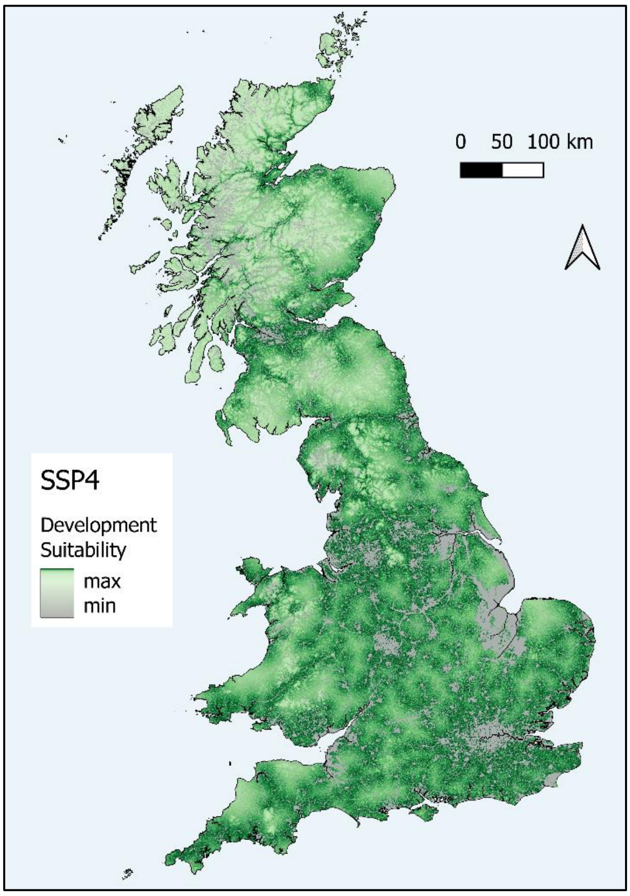

Figure 5. UDM national suitability surface for SSP4.

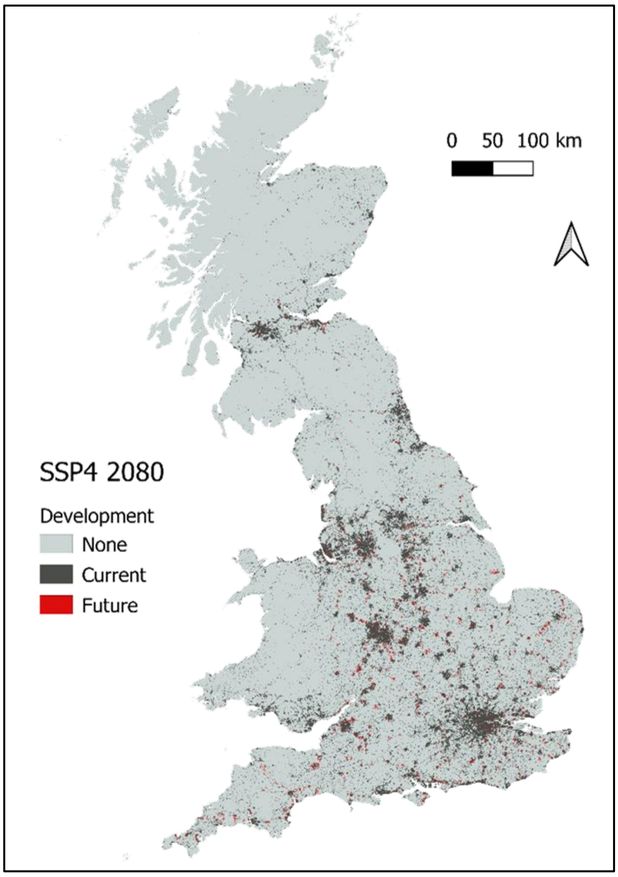

Figure 6. UDM SSP4 predicted urban development for 2080.

3.2 Property Damage

As part of the UK OPENCLIM project the city of Norwich (England) was selected as a case study to assess the impact of climate driven pluvial flooding on future urban development. In order to achieve this UDM outputs for SSP4 covering the city were used to parametrise an UFG run to generate 2080 spatial configuration of buildings, road and urban green space which was then amalgamated with the existing urban digital map data of the city (Figure 7).

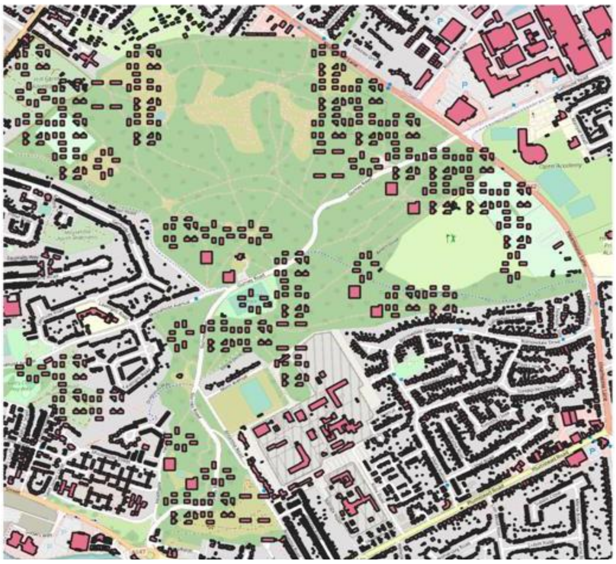

Figure 7: UFG generated 2080 buildings amalgamated with existing urban digital map data for the city of Norwich.

The amalgamated urban digital map data and UFG generated 2080 urban fabric were then used within the CityCAT hydrodynamic urban flood model that simulates the flow of surface water in the presence of urban features such as buildings (Iliadis et al, 2023). Figure 8 shows the result of the CityCAT modelling for a 40mm rainfall event applied to the city of Norwich using the 2080 building layout generated by the UFG. It reveals that most of the buildings in the new development at the centre of Norwich (shown in green) would be unaffected by flooding that would occur as a result of the 40mm rainfall event. However, a number of small pockets of new development would be inundated by up to 1m of flood water, although the greatest impact would be on existing buildings within the city.

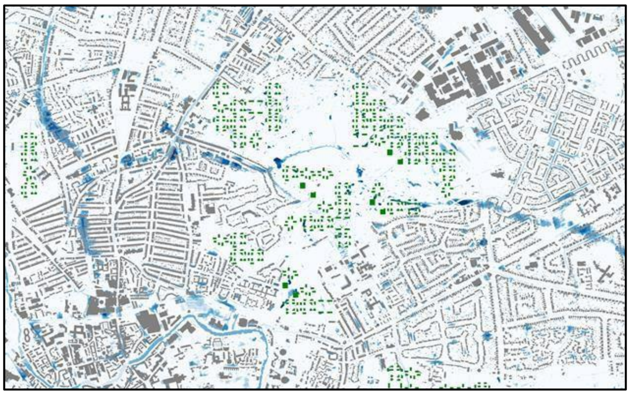

Figure 8: Modelled flooding for Norwich showing depth of inundation on existing and 2080 new development.

One advantage of the being able to include plausible configurations of buildings, roads and urban green space from the UFG is that it allows individual features to be included within impact analysis and calculations of damage. For example, output from the UFG can be used to recognise the new buildings that would be directly affected by the pluvial flood event, and only have those (along with existing properties that would be flooded) included in an economic assessment of damages. Figure 9 shows the result of such a procedure where for the pluvial flood event of Figure 8 only those buildings that would actually experience flooding are included in maps showing the number of residential properties per-hectare that would experience flooding (Figure 9:left) and the subsequent economic cost (£) of flooded properties per-hectare (Figure 9:right).

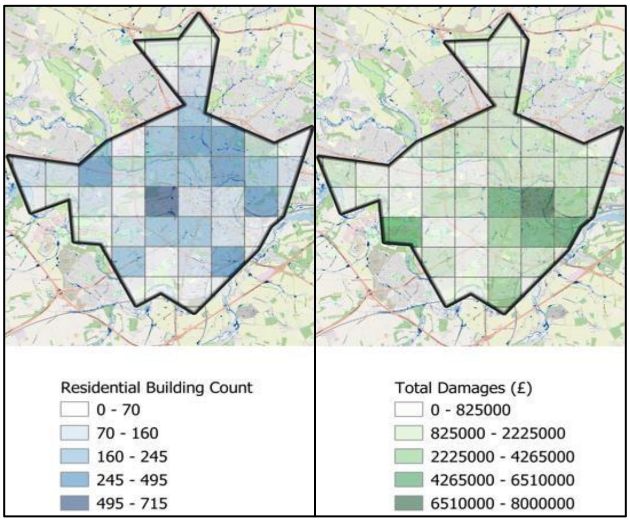

Figure 9: Number of residential properties and cost of flooding per-hectare in the centre of Norwich.

3.3 Adaption via Infrastructure Investment

It has been argued that one way that the risk and impact of future surface water flooding may be reduced within the built environment is via improved infrastructure investment in urban drainage schemes (D'Ambrosio et al, 2022). In order to investigate this UDM was run to generate an entirely new urban conurbation that could accommodate ~100,000 inhabitants.

The land assigned for development along with the corresponding density of development (dwellings per-hectare) was used to parametrise the UFG in order to generate a full synthetic urban conurbation. Using the CityCAT model a three hour ~100mm rainfall surface water flood was simulated. Figure 10 shows the result of this process; darker shades of hatching correspond to a higher number of dwellings per-hectare and hence different residential building types, larger in size and with a smaller proportion of urban green space than lighter shaded (hatched) areas. Figure 10 also shows the flow paths and depth of flood water inundation across the synthetic urban conurbation for the three-hour event, showing in several place significant flooding of up to 5meters in depth.

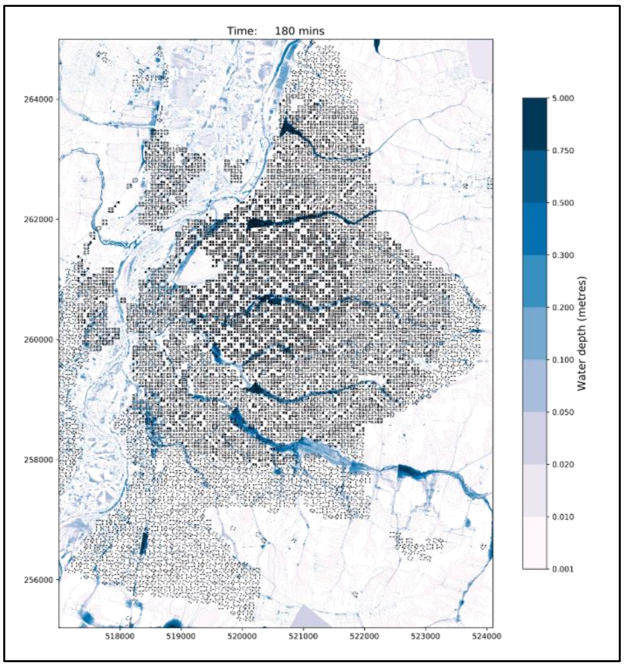

Figure 10. Flood inundation depths for a synthetic new urban conurbation generated by the Urban Fabric Generator.

One advantage of the CityCAT model is that it can run in an urban drainage mode where a storm sewer network along with corresponding urban drainage inlets can be used within the flood modelling. In order to investigate the potential adaption of the new urban conurbation in terms of the urban drainage system, the synthetic urban conurbation was used to generate a synthetic urban storm sewer network, where road centre lines from the UFG was used to derive the synthetic storm sewer network. Two different scenarios of urban drainage configuration were investigated. The first was a storm sewer network with a number of drainage inlets corresponding to current design best practice. The second was a doubling of the number of drainage inlets to the storm sewer network. Figure 11 shows the UFG building, roads and urban green space configuration generated for a portion of the full synthetic urban conurbation. The top sub-figure on the left shows the spatial distribution of drainage inlets for the standard storm sewer design, while the bottom sub-figure on the left shows the same synthetic urban area but with the number of inlets is doubled.

Figure 11 also shows in the right sub-figures the resultant surface water flooding experienced when the CityCAT model is run for the two different configurations of inlets. It is clear that both the spatial extent and distribution of flooding is significantly reduced by doubling the number of inlets (bottom sub-figure) compared to the standard design (top-figure). Furthermore, while flooding is not entirely removed by doubling inlets, the depth of inundation and the speed of water flow is noticeably less than in the flooding experienced by standard design simulation.

4. Conclusion

CA spatial models provide a powerful means by which future urban development can be simulated to reveal plausible patterns of development. The outputs of such models are increasingly being used within climate hazard risk and impact assessment studies to understand not only the impact of future climate extremes on the exiting urban fabric but also the future development that we will see as a result of population change. However, certain types of climate risk and impact studies require more detailed information on the spatial pattern of urban development rather than whether an area of land will or will not be developed.

In this paper the utility of Urban Fabric Generator (UFG) that uses an empirically based procedural downscaling approach to convert future simulated development densities from a CA model to plausible spatial configurations of buildings, roads and urban green space has been demonstrated. The results of two case studies clearly demonstrate the utility of UFG. The UFG allows detailed understanding of the potential consequences of where and what type of new development is undertaken within existing urban conurbations with regards to being able to highlight at a granular spatial scale areas prone to future hazards (e.g., flooding). Moreover, the UFG allows far more precise economic damage appraisals to be undertaken that explicitly include future buildings with the capability to distinguish those that will and will not be at risk within the same spatial unit (e.g., 1-hectare grid cells in the case of this study). Finally, the UFG also allows infrastructure adaptions to be explored and quantified in order to allow cost-benefit appraisals of interventions for future urban development to be undertaken.

The UFG approach can potentially be developed in several directions in the future. An obvious extension is to fully integrate the UFG into a multi-scale start-to-end workflow of models for use within climate impact and wider sustainability studies. In this regard, the UFG would form the final downscaled component of future development in an approach such as the UIAF developed by Ford et al (2019). A further refinement would be to allow the UFG to 'interpolate' urban designs and layout by the use of generative AI methods such as Generative Adversarial Networks (GANS) (Fedorova, 2021; Gan et al, 2024). This would potentially allow new spatial designs and configurations to be explored that could be parameterised both by existing UK data but also from best practice design internationally using cities that are adopting different urban design principles to address climate change hazards.

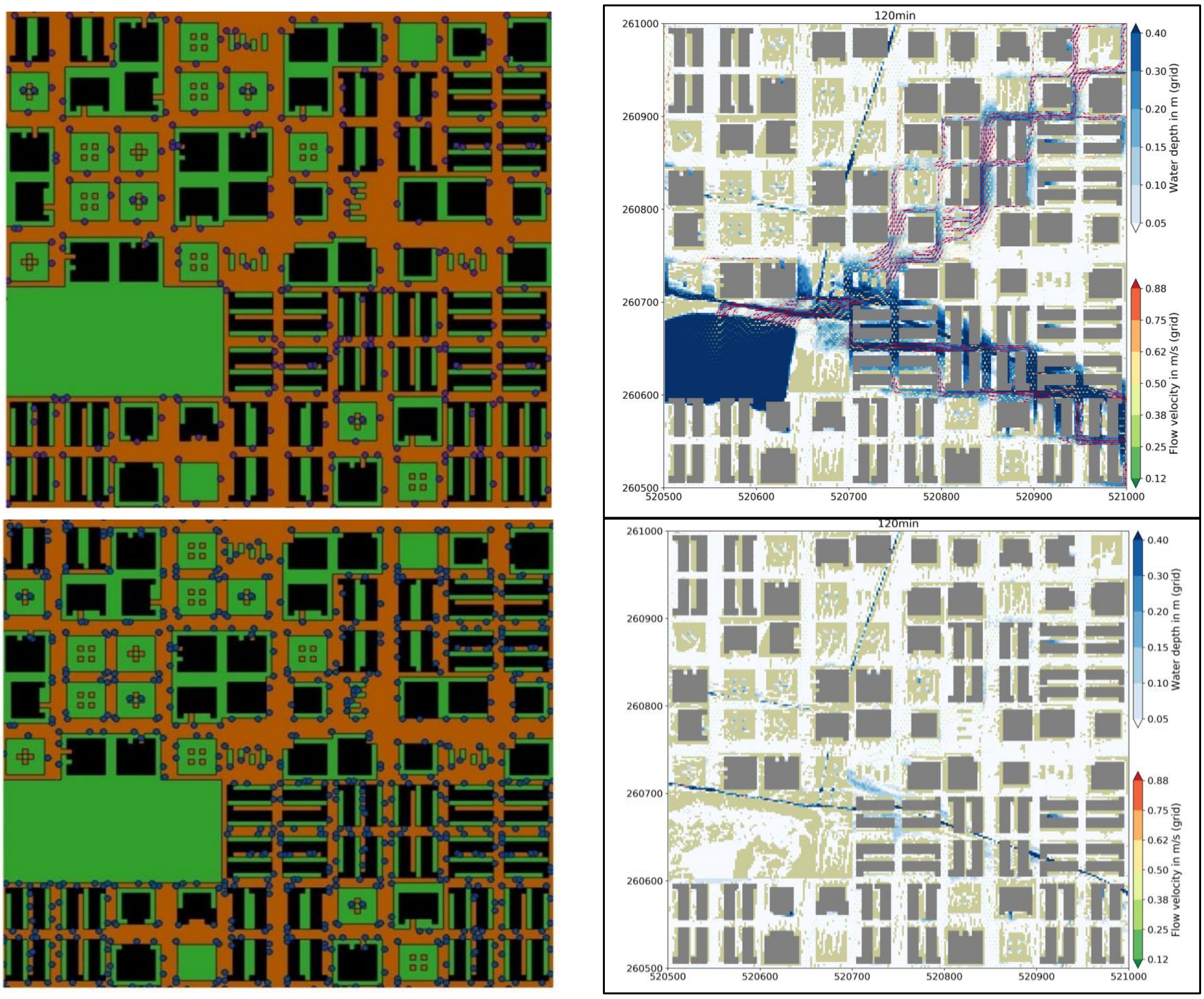

Figure 11. UFG outputs for a 25-hectare area (500-by-500m) of the new urban conurbation in Figure 10. Top left: UFG urban fabric with standard design specification of urban drainage inlets, Bottom left: UFG urban fabric with doubled urban drainage inlets. Top right: CityCAT results for standard design specification of urban drainage inlets. Bottom right CityCAT results for doubled urban drainage inlets.

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