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Developing spatial prioritization criteria for integrated urban flood management based on a source-to-impact flood analysis

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Abstract

Integrated flood management is essential in urban planning in order to align flood protection and mitigation with the complex social and physical infrastructure in cities, and involves the management of surface water by retaining, reusing and transferring it along its pathway across multiple infrastructure systems. However, despite many potential flood management solutions (natural and engineered), spatial prioritization to implement these solutions from a catchment perspective remains difficult. A transferable, source-to-impact flood analysis is developed to identify locations with high flood hazard and areas contributing the most to this hazard, which is used as a basis to define spatial prioritization criteria for flood management intervention. The analysis was applied to Newcastle-upon-Tyne (UK) and included a spatial rainfall cell dependency analysis with the hydrodynamic flood model CityCAT to identify locations contributing the most to flood hazard. Locations within the study area were then classified based on four criteria: (i) contribution to the total flood extent; (ii) maximum flood depth contribution; (iii) coverage of greenspaces and roads by the flood extent; and (iv) likelihood of flood exposure. The results illustrate the importance of considering the catchment holistically and also identify spatial linkages to manage flooding and its potential impact on, and interaction, with different infrastructure systems. Criteria can be combined in different ways to guide spatial prioritization depending on the specific flood management objectives (e.g. Blue-Green infrastructure). The concept presented offers a basis for developing a systematic, high-level approach to inform spatial prioritization for flood management intervention, which can be applied prior to developing actual flood alleviation schemes. In doing so, the approach will help identify opportunities to combine multiple urban systems and allocate resources more efficiently.

Keywords

Path management, catchment-based, urban flooding, connectivity, land cover, Blue-Green infrastructure

1. Introduction

With the combination of increasing urbanisation and climate change, the frequency and consequences of rainfall, surface water, and flood events are likely to exacerbate, and many of the existing flood management practices and infrastructure, will be put under significant pressure and risk of failure (IPCC, 2014; UNISDR, 2015). As a result, traditional flood mitigation strategies will need to be supplemented with adaptation strategies to enhance flood resilience in cities. To this end, integrated flood risk management is essential. Integrated flood risk management aims to combine innovative adaptation solutions, make infrastructure systems more interoperable (Vercruysse et al., 2019), and bring together multiple stakeholders by recognizing and utilising interrelationships between different sectors (Brown, 2005; Hall et al., 2003; Merz et al., 2010).

Despite the availability of innovative adaptation solutions for flood management, both at local scales (e.g. sustainable urban drainage systems (SUDs)) (Fletcher et al., 2015) and larger scales (e.g. Sponge Cities) (Li et al., 2018), studies have pointed out that there is an “adaptation deficit” in these solutions (Ernst and Preston, 2017; Preston et al., 2013) and wider integrated flood management (Kuller et al., 2017). To explain this deficit, studies have identified several socio-political barriers to the adoption of SUDs, including the lack of information and associated perceptions of all stakeholders, split regulatory and management responsibilities (e.g. maintenance), difficulty of capturing value, and uncertainty about performance and capacity of physical systems (Hoang and Fenner, 2016; O’Donnell et al., 2017a; Schuch et al., 2017; Staddon et al., 2017).

The physical basis of these barriers lies in the fact that within integrated flood management, flood water is not dealt with at a discrete location, but along its pathway (i.e. retaining, reusing, diverting and transferring flood water). This shift towards “path management” implies that adaptation solutions cover different infrastructure systems and cross multiple socio-political boundaries. To overcome these barriers and facilitate prioritization and decision-making to make flood management more interoperable, it is key to have informed insights into the flood dynamics in cities, i.e. where is the highest potential flood risk; where is the source of the excess water; and, critically, how does this information link to identifying priority areas for flood management intervention (Vercruysse et al., 2019)?

Many flood models have been developed over past decades (Sanders, 2017; Teng et al., 2017), which have helped to better understand urban flood dynamics and assess the impact of interventions and management options on flood levels. Nevertheless, predicting and modelling pluvial flood hazard is complex because it depends on many factors (e.g. topography, impervious surfaces, and rainfall characteristics) and scales (temporal and spatial). As a result, flood models vary strongly in complexity and the type of information they provide. Generally, there are three types of models to estimate flood extent and/or depth: (i) empirical models based on historic records; (ii) hydrodynamic models (1D, 2D and 3D) and (iii) simplified models (Teng et al., 2017). Hydrodynamic models are especially interesting in the context of integrated, interoperable flood management, because the high level of detail in those models allows for simulating interactions between different infrastructure systems, e.g. to evaluate the impact of BGI (Blue Green Infrastructure) (Morgan and Fenner, 2017) and other infrastructure modifications in terms of storm drain inlets (Bertsch et al., 2017), or test the impact of climate change scenarios on different infrastructure systems (Pregnolato et al., 2017). However, it remains challenging to apply flood models to guide integrated flood management as part of the increasing need to adopt a “whole catchment” approach (CaBA, 2018). A significant challenge in the use of urban flood models is to produce context-specific knowledge that will drive actual adaptation; there is a need to align the use of urban flood models with the complex (spatial) decision-making process in integrated flood management that goes beyond scenario-testing (Sanders, 2017).

This study investigates how flood models can be aligned with the systematic identification of priority areas for interventions for flood management at the catchment scale. A transferable, source-to-impact flood analysis is developed to identify locations with high flood hazard as well as areas that contribute the most to this hazard, and how this information can be used to guide spatial prioritization in flood management is explored. In the following section, the case study catchment and flood model are described alongside a methodological description of the characterisation of potential priority criteria. In the subsequent sections, the results are presented and discussed in terms of how different prioritization criteria can be used and combined to approach flood management from a catchment perspective.

2. Methodology

2.1 Case study

The urban core of Newcastle-upon-Tyne in north-eastern England (UK) was used to develop the methodology. The study area is defined by a natural drainage catchment (9.15 km^2)

(Figure 1), with the public park Town Moor dominating the upper part of the catchment, while the lower catchment is characterised by dense historical buildings and residential areas.

Due to its vulnerability the city has been studied extensively in relation to flooding, especially as part of the Blue-Green Cities and Urban Flood Resilience research projects (Blue-Green Cities Research Project, 2016; Urban Flood Resilience Research Project, 2018). For example, previous studies identified multiple benefits that could arise from implementing pre-selected BGI across the city (Morgan and Fenner, 2017; O'Donnell et al., 2017b) (Figure 1). Furthermore, within the city centre, several development projects are being delivered/developed which strongly focus on BGI and sustainable water management solutions (e.g. Newcastle Helix and East Pilgrim Street Development in Figure 1) (Helix, 2019; Lawless, 2016a, 2016b). Therefore, Newcastle forms a good case study to investigate how systematic identification of spatial priority areas for flood management align with actual decision making in practice.

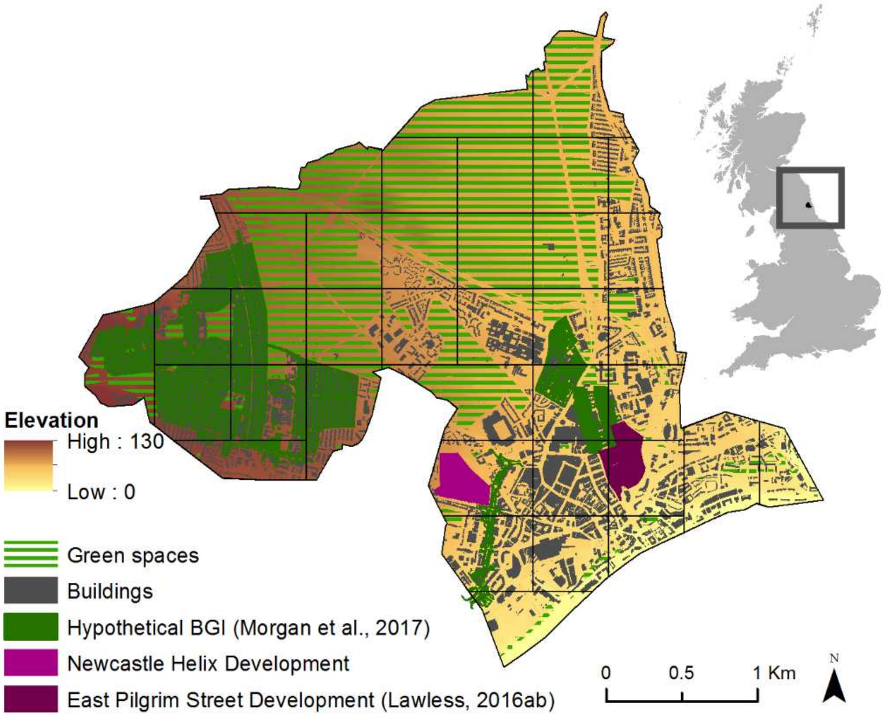

Figure 1: Overview urban core Newcastle-Upon-Tyne (Contains OS data © Crown copyright and database right 2019).

2.2 Source-to-impact flood analysis

To test the contribution of specific areas to the generation of water runoff, i.e. to quantify how much individual areas contribute to the total flood extent during a simulated event, a source-to-impact flood analysis was designed based on a systematic rainfall cell dependency analysis. To the authors' knowledge, this type of analysis has not previously been applied in urban catchments, but a similar approach has been used in a rural catchment (Ewen et al., 2013). The modelling was carried out with CityCAT because of its detailed performance and earlier application to Newcastle (Glenis et al., 2018), but the approach can be applied to any hydrodynamic urban flood model with spatial rainfall input data. The analysis consists of four steps, and is described in detail below (Figure 2):

(i) *Grid representation*: divide the study area into approximately equal cells;
(ii) *Baseline scenario:* run model to generate flood depths for equal rainfall across all cells;
(iii) *Rainfall cell dependency analysis:* run model omitting rainfall in an individual cell;
(iv) *Source identification:* compare the baseline with the cell scenarios.

For (i) the catchment was divided into 37 cells (0.5km x 0.5km, approximately) which are considered as potential "source areas" for surface runoff generation. Second, a baseline scenario (ii) was obtained of estimated flood depths in the study area by running CityCAT for a 1-in-50 year rainfall event with a duration of 60 minutes (Figure 2). Using the grid, a rainfall cell dependency analysis (iii) was performed by running the model multiple times (i.e. one run per cell, 37 in total), while each time systemically omitting the rainfall in one single cell, to simulate a situation where all rainfall is captured within that cell and not contributing to runoff generation (Figure 2). Finally, (iv) maximum flood depths simulated for the baseline scenario were compared with the maximum flood depths simulated for the cell-scenarios by subtracting both to create difference maps:

$$F_i = Fd_{bs}^R - Fd_i^R \qquad [1]$$

With F_i the flood depths generated by cell i, Fd_{bs}^R the maximum flood depths modelled for the baseline scenario and Fd_i^R the modelled maximum flood depths for the scenario, whereby the rainfall in cell i is omitted, simulated for an R rainfall event (1/50 years) and i ranging between 1 and 37.

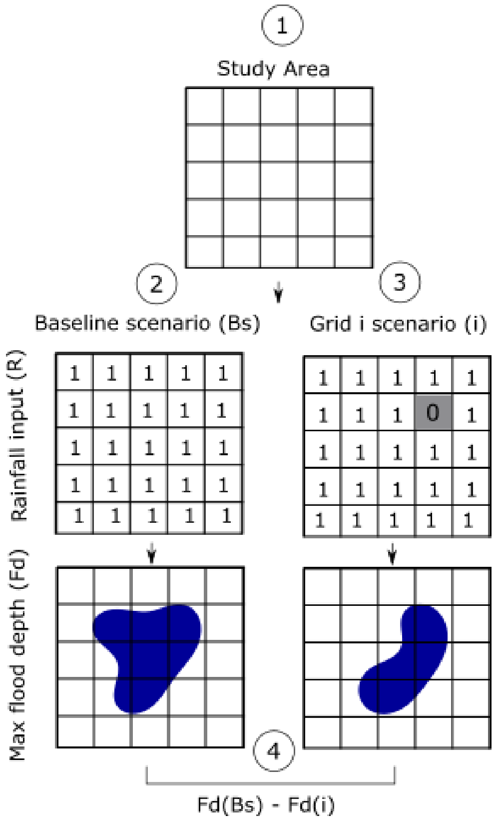

Figure 2: Illustration of four steps in source-to-impact flood analysis: (i) convert study area into equal cells; (ii) generate flood depths for a baseline scenario (Fd_{bs}^{R}) (equal rainfall R in entire catchment); (iii) perform cell dependency analysis by running flood model i times whereby rainfall (R) in the ith cell is set to zero (Fd_{i}^{R}); and (iv) subtract Fd_{bs}^{R} and Fd_{i}^{R}, resulting in flood extent generated by cell i (Fd_{i}).

2.3 Spatial intervention priority criteria

The information obtained through the source-to-impact flood analysis (Section 2.2) provides in-depth information on the spatial connection between areas characterised by flood hazard and areas contributing to this hazard, which creates opportunities to develop measures to prioritize locations for flood management at the catchment scale. To explore how F_i can be used to guide spatial prioritization for flood management intervention, four potential intervention priority criteria were identified, each providing another level of information related to the flood impact caused by each cell (Table 1). Criteria 1 and 2 are based solely on the physical reduction of flooding, while criteria 3 and 4 also include land use and exposure information to align with the type of information that essential for flood management practitioners to justify the building of flood alleviation schemes (e.g. flood exposure to households and roads) (Zevenbergen et al., 2018).

Table 1: Spatial priority criteria: criteria values are estimated per cell in the study area grid (Figure 1).

Criteria		Calculation	Description
1	Flood extent generated	$Farea_i$ = Area(F_i)	$Farea_i$ is the area (m^2) covered by surface water in the difference map F_i
2	Maximum flood depth	Fd_{maxi}= max(F_i)	Fd_{maxi} is the maximum depth (m) occurring in the difference map F_i
3a	Green space flooded *	$Farea(greensp)_i$	$Farea(greensp)_i$ is the area (m^2) of green space covered by surface water in the difference map F_i
3b	Major roads flooded **	$Farea(majorR)_i$	$Farea(majorR)_i$ is the area (m^2) of major roads covered by surface water in the difference map F_i
3c	Minor roads flooded**	$Farea(minorR)_i$	$Farea(minorR)_i$ is the area (m^2) of minor roads covered by surface water in the difference map F_i
4	Likelihood of flood exposure to buildings	$E_i = Elow_{bs} - Elow_i$	E_i is the number of buildings that changed from high/medium likelihood to low likelihood of exposure by omitting rainfall in cell i $Elow_{bs}$ and $Elow_i$ the number of buildings at low likelihood of flood exposure in the baseline and cell i scenarios respectively

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Criterion 1: Flood extent generated per cell

The total flood contribution (m^2) generated by a cell (i.e. the flood extent that is avoided when all rainfall is retained in that cell) is the most basic measure to guide spatial prioritization for flood management, if the main management objective is to reduce overall surface water flooding. Flood management interventions can then be focussed on the cells generating the widest surface flooding by retaining rainfall as much as possible (e.g. with retention ponds or green roofs) (Gregoire and Clausen, 2011; Schubert et al., 2017). Therefore, the first priority criterion is the flood extent generated per cell during the simulated rainfall event, and is defined as the area delineated by the difference map in maximum flood depths between the baseline and a specific cell scenario (Table 1).

Criterion 2: Maximum flood depth generated per cell

While flooding can have an impact on an extensive area across the catchment, it is the deepest surface flooding that can cause the most damage and is, in combination with velocity, the biggest threat to people (Balica et al., 2009). Therefore it is often not only important to consider locations that have a significant impact on the total flood extent, but also to focus flood management measures in locations (cells) that generate localised (small extent) but deep surface flooding which can potentially cause more damage. The contribution of each cell in terms of flood depths is defined in the second priority criteria as the maximum flood depth associated to the flood extent (Table 1).

Criterion 3: Land use types flooded

Besides reducing the flood extent and/or depth, flood management is most often focussed on reducing flooding primarily in particular locations depending on the land use covered by the flood extent. For example, extensive flooding that mostly covers green space might be considered less of a protection priority, or require a different type of intervention, than a location causing flooding on an important road. To address this, the flood extent per cell was also expressed in terms of land use flooded to form a third type of priority criterion. In this study, green spaces and the road network (major and minor roads) were selected (Table 1). However, future analysis could include other specific spatial land use types (e.g. open spaces, commercial areas, and public property areas).

Criterion 4: Likelihood of flood exposure to buildings caused per cell

The previous criteria (1-3) are primarily based on the output of the source-to-impact analysis. This information can also be combined with an exposure analysis describing more explicitly the relationship between flood dynamics and the likelihood of individual buildings to be exposed to the impact of flooding. To this end, a final criterion for spatial prioritization for flood management intervention is defined by the exposure of buildings to flooding (Table 1).

The flood exposure calculations for buildings were done with the flood exposure calculator developed by (Bertsch, 2019). Using readily available data formats (shapefiles and CSV files) the flood exposure calculator is applicable independently of any GIS or flood modelling software. Available as a Jupyter notebook the tool and open-source code can be downloaded from [https://github.com/hydrob/Flood-Exposure-Calculator]. The tool performs a spatial analysis using detailed building geometries and high resolution water depth data without conducting any aggregation or simplification of the input data. In a first step, the tool generates a buffer for each building for the purpose of extracting water depth information from cells closest to the building footprint. Hence, a buffer width of 3 m (i.e. 150% of the horizontal grid resolution) was applied (figure 5.19 in Bertsch (2019)). Subsequently, the extracted water depth information is used to calculate the mean and maximum depth in order to classify the exposure likelihood based on table 5.2 in Bertsch (2019). The automated calculation of the exposure for all 12,599 buildings and all 38 scenarios in this study required approximately six hours.

2.4 Criteria comparison and combination

Criteria (1-4) were compared in terms of what type of information they can provide and how they differ towards informing prioritization for flood management intervention within a wider catchment area. To enable spatial comparison between criteria, the output criteria values were all classified into three classes (low, medium, high priority) based on the Geometrical Interval Classification method in ArcGIS. For all criteria, the highest value means the highest priority, except for the greenspace coverage: a higher coverage of greenspace by the flood extent represents a lower priority.

To assist prioritisation and allow different flood management preferences to be examined, and subsequent locations to be determined, it is critical that criteria can be combined (Meerow and Newell, 2017). For example, one approach could be to prioritise the modification of existing BGI for managing surface runoff. In that case, retaining rainfall in locations (i.e. cells) that generate the widest flood extent with a dominant coverage of greenspace, while also causing the highest exposure to buildings, could offer the greatest potential of reducing flood risk by modifying the flooded green space to store water. To illustrate a possible method to combine criteria that can help prioritize the most suitable locations for this approach, a simple three-step ranking of criteria 1, 3a and 4 was carried out. First, all cells were ranked three times from high to low values on criteria 1, 3a and 4, each time attributing ranking numbers to each cell (rank number 1 = cell with highest flood extent, exposure or green space cover) (Table 2). Then, the three ranking numbers of each cell were summed to provide a single value reflecting the locations with the highest priority for enhancing existing green spaces for flood management (i.e. lowest summed rank number = highest priority).

Table 2: Example of the approach used to identify priority locations for BGI based on criteria 1, 3a and 4.

Cell	Flood extent (1)	Flood exposure (4)	Green space cover (3a)	Sum rank number
B	1 (highest m^2)	1 (highest m^2)	2	4 (Highest priority for BGI)
A	3 (lowest m^2)	2	1 (highest m^2)	6
C	2	3 (lowest m^2)	3 (lowest m^2)	8 (Lowest priority for BGI)

3. Results

3.1 Baseline scenario flood hazard

Flood depths were estimated for the baseline scenario (i.e. homogeneous rainfall across the catchment). The highest flood depths converge around a few flow paths across Town Moor and local hotspots in the lower part of the catchment (Figure 3a). The cells in the middle and lower part have the largest area covered by flood depths >0.3m. However, a different pattern reflecting flood hazard is apparent when considering the results from the exposure analysis, whereby the areas with the highest risk of exposure to buildings are situated to the west and across the lower part of the catchment (Figure 3b).

These results provide insights into the potential flood hazard within the city centre and how this hazard can be interpreted differently depending on the type of information used. These findings are very valuable when assessing the impact of flooding on people and infrastructure, and testing different scenarios for flood management options (e.g. test the effect BGI in a particular location on flood depths). However, from an integrated management perspective, these flood maps are not directly useable, because they do not provide source-to-impact information; it remains a matter of trial-and-error through scenario-testing to identify priority locations for flood management at the catchment scale.

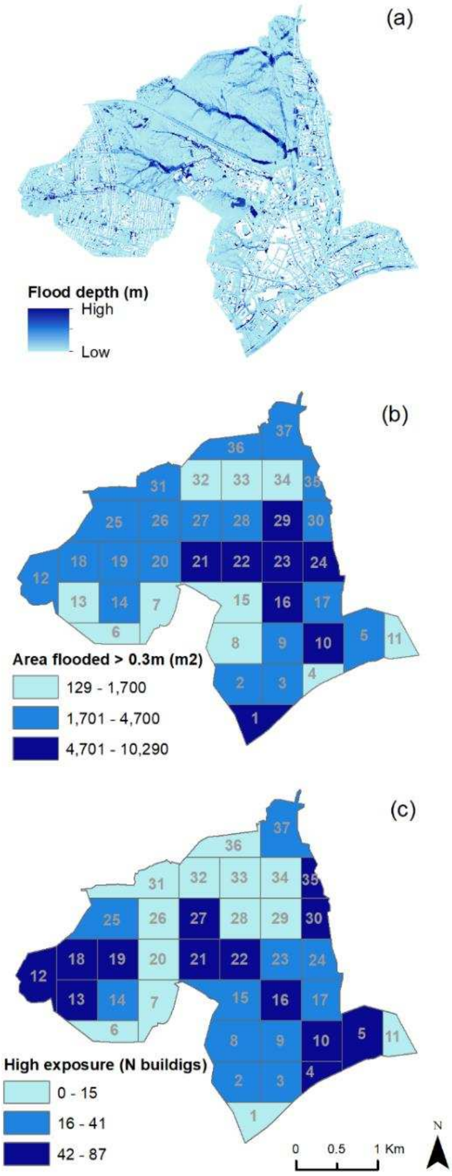

Figure 3: Baseline flood modelling results for a 1/50 year rainfall event of 60 minutes in the urban core of Newcastle using CityCAT: (a) maximum flood depths, (b) number of points (i.e. 2 m cell) with an estimated flood depth >0.3m (flood hazard), (c) number of buildings at risk of high exposure. Numbers in figure (b) and (c) refer to the labels of the rainfall cells.

3.2 Source-to-impact flood analysis

The source-to-impact analysis was developed to systematically assess the impact of individual cells on flood hazard locally and further downstream. The results of the source-to-impact flood analysis can be visualised by the difference maps between the maximum flood depths simulated in the baseline scenario (Figure 3a) and the flood depths simulated for the different cell scenarios. An example is illustrated in Figure 4, which shows the difference map for the Cell 12 scenario. It can be observed that the flood extent generated by Cell 12 reaches across multiple cells, with an area of 0.39 km^2 and a maximum flood depth of 1.4m (Figure 5-6). The difference maps of the other scenarios are available as supplementary material.

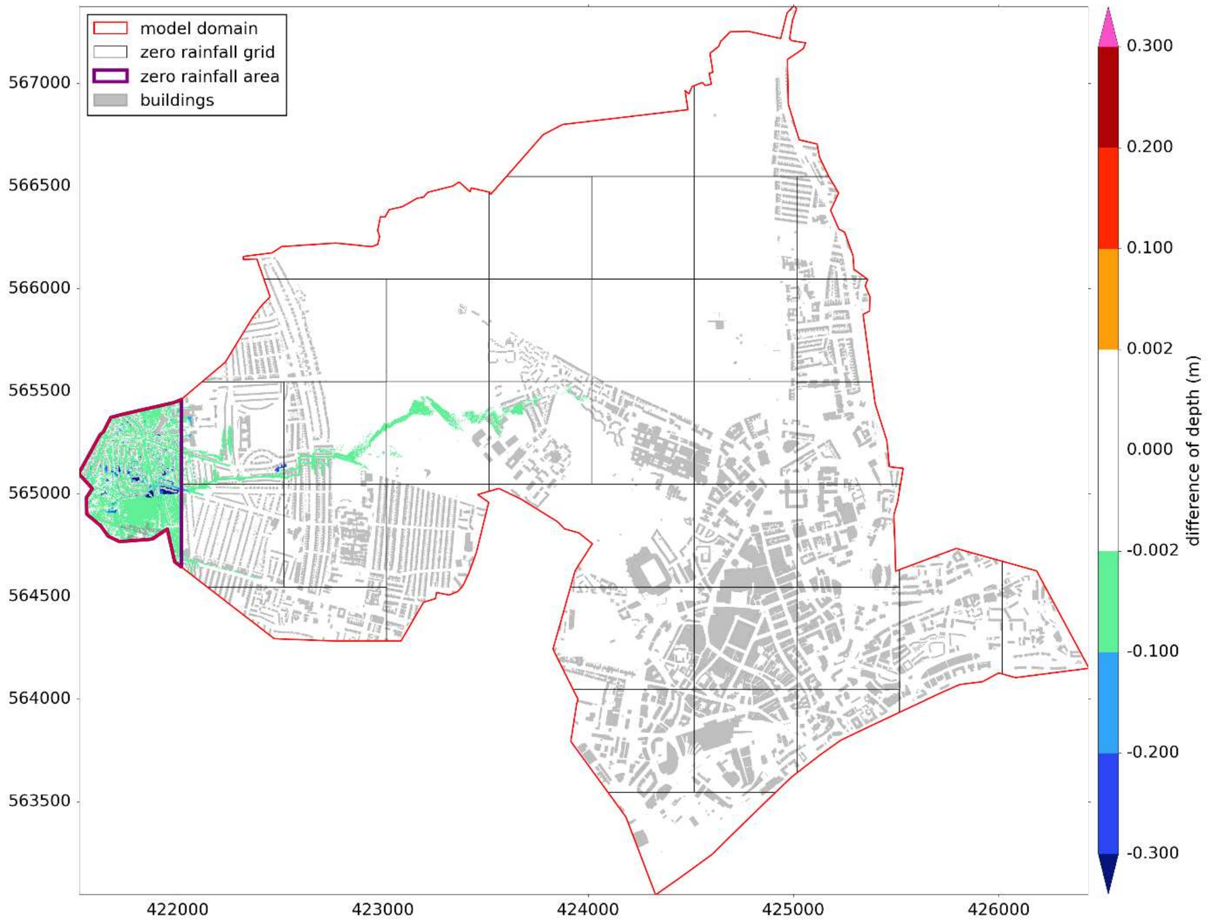

Figure 4: Example of difference map between maximum flood depths simulated for the baseline scenario and cell 12 scenario (i.e. rainfall in cell 12 omitted), illustrating the flood extent and flood depths generated by this cell. (Contains OS data © Crown copyright and database right 2019).

3.3 Spatial intervention priority criteria

As described in the methodology, the difference maps for each cell scenario resulting from the source-to-impact analysis were used to extract four types of intervention priority criteria.

Criterion 1: Flood extent

The flood extents per cell in the difference maps was calculated. As expected, the cells in the upper part of the catchment are characterised by the highest flood extent, i.e. contribute to the widest surface flooding (Figure 5a).

Criterion 2: Maximum flood depth

The difference maps were further used to extract the maximum flood depths associated with the flood extent per cell. In general, cells in the downstream part of the catchment generate the highest flood depths (Figure 5b).

Criterion 3: Land use coverage of flood extent

Linking the flood extent per cell to land use classes allows for further investigation of the interactions between flood dynamics and existing urban infrastructure systems (Figure 5c-e). In general, the flood extent related to cells in the upper part of the catchment mostly cause surface flooding on green spaces, whilst some (e.g. cell 31) also extend onto the major road network (Figure 5c). The major road network is mostly affected by surface flooding generated by local rainfall in the central part of the catchment (Figure 5d), while flooding on minor roads is predominantly generated by cells in the eastern part of the catchment (Figure 5e).

Criterion 4: Likelihood of buildings exposure

For the final criterion, the likelihood of buildings exposure to flooding was estimated for each scenario (difference between the baseline scenario in Figure 3c and cell scenarios). The results are summarized as the number of buildings at high to medium likelihood of exposure that would become low likelihood if the rainfall in a cell is omitted (Figure 5f). Similar to the flood extent covering minor roads, flood exposure to buildings is predominantly caused by cells in the eastern and central part of the catchment.

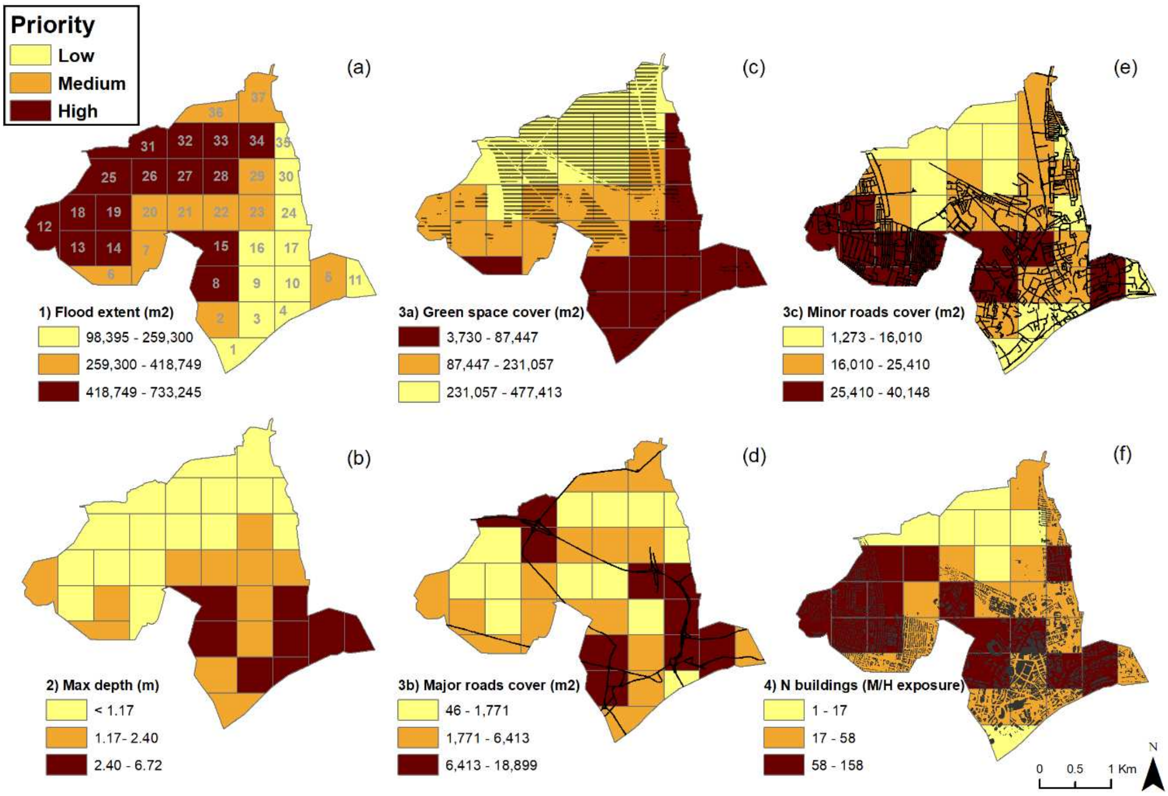

Figure 5: Classified spatial prioritization criteria per cell: (a) criterion 1: flood extent; (b) criterion 2: max flood depth; (c) criterion 3a: greenspace cover by flood extent; (d) criterion 3b: major roads cover by flood extent; (e) criterion 3c: minor roads cover by flood extent; (f) criterion 4: flood exposure (number of buildings at medium (M) to high (H) likelihood of exposure). Locations of greenspaces, roads and buildings marked in black, Contains OS data © Crown copyright and database right 2019.

3.4 Criteria comparison and combination

Spatial comparison of the priority location indicated by each criterion based on the three classes (low, medium, high) reveals that no consistent pattern exists, i.e. no consistent priority location for intervention can be determined in that all the criteria indicate the same cell (Figure 5). However, most criteria indicate priority locations for flood management in cells characterised by medium to low flood hazard (Figure 3). This observation becomes especially clear when directly comparing the cell values for flood hazard and all criteria (Figure 6). Furthermore, there are a few cells that are classified as high priority areas based on all criteria (e.g. cell 8 and 14, grey bars in Figure 6). These areas represent locations that are classified as high (to medium) priority across all criteria – if no preference or specific objective for the flood management approach is considered.

However, as noted earlier, there are multiple approaches to flood risk management both in terms of objectives and type of intervention. To illustrate how the different criteria can be combined depending on the desired flood management approach, criteria 1, 3a and 4 were combined to guide spatial prioritization for BGI (Figure 6). Based on the simple three-step ranking methodology described in Section 2.4, cells in the upper west part of the catchment are locations that should be prioritized for use of existing green spaces as BGI solutions for flood management. More specifically, Cell 18 and 19 are identified as locations with the highest (H) potential of reducing flood hazard using modification of the existing green space within these cells (green bars in Figure 6). On the other hand, while cells 9 and 11 contribute significantly to the flood extent on minor roads and generate deep flooding respectively, the absence of green space and moderate exposure for buildings, indicate that these cells can be considered as low priority areas in the context of BGI solutions for flood management. Combining this information in a map (Figure 7), a clear zonation of prioritisation for BGI solution is provided – which can help steer management approaches across the grid.

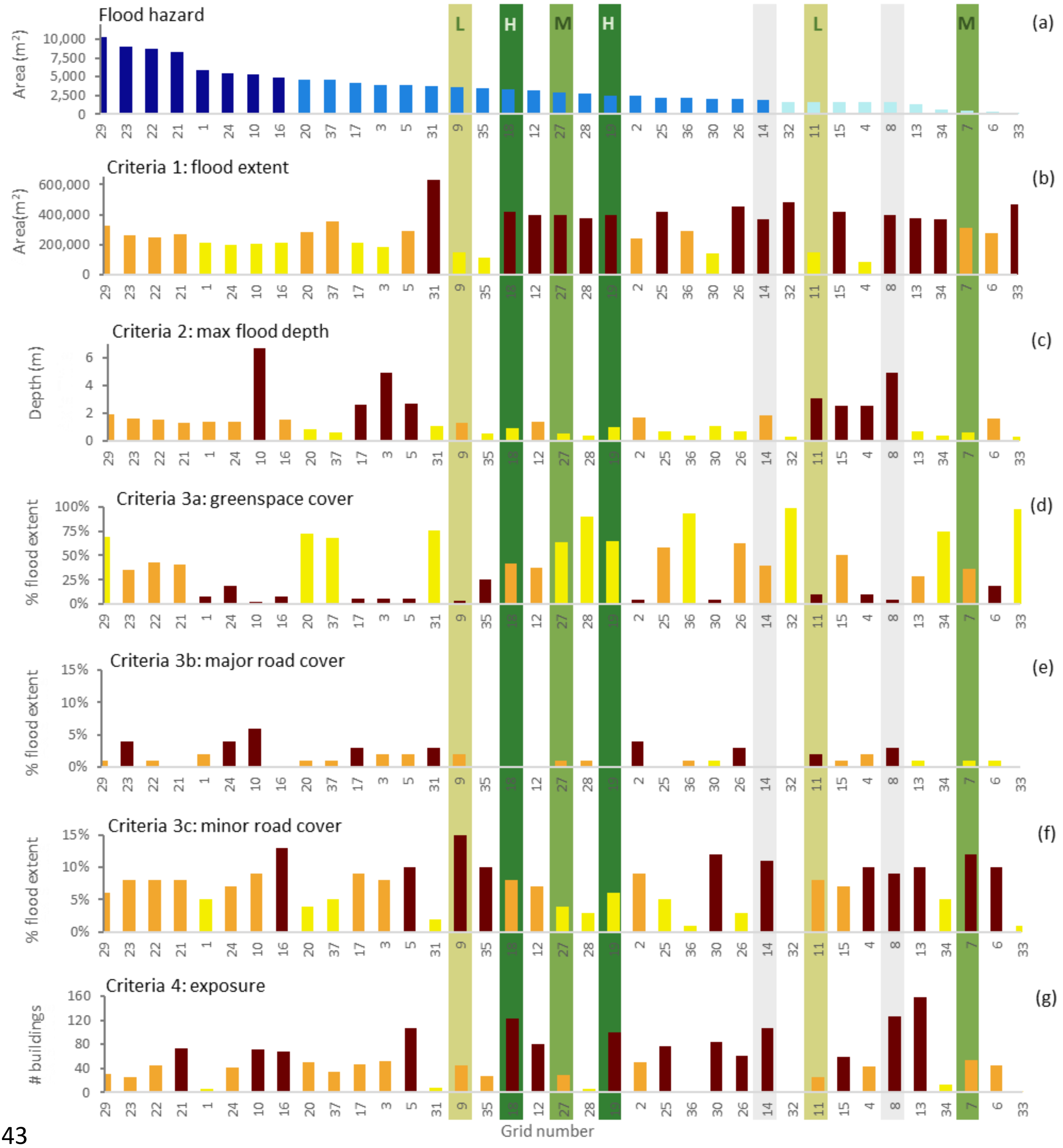

Figure 6: Summary statistics per cell: (a) flood hazard: area > 0.3m in baseline scenario per cell; (b) criterion 1: flood extent; (c) criterion 2: max flood depth; (d) criterion 3a: greenspace cover by flood extent; (e) criterion 3b: major roads cover by flood extent; (f) criterion 3c: minor roads cover by flood extent; (g) criterion 4: flood exposure. Light grey bars indicate cells 14 and 8 which show high priority on most criterion; green bars indicate priority areas for BGI (H: high, M: medium, L: low priority), as visualised in Figure 7.

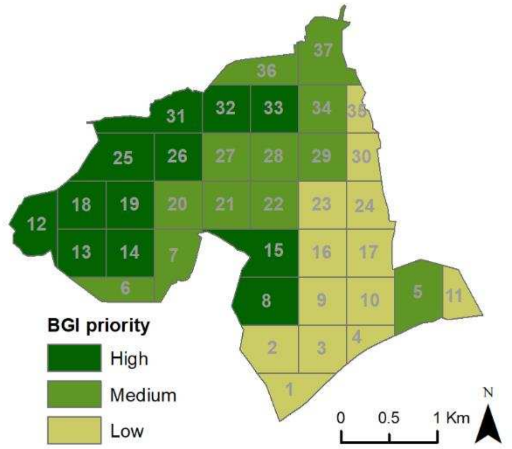

Figure 7: Cells classified as priority areas for BGI in Newcastle based on three-step ranking of criterion 1, 3a and 4 (following approach illustrated in Table 2).

4. Discussion

To approach flood management from a catchment perspective and identify priority locations for flood management intervention *prior* to developing flood alleviation schemes, insights are needed into the flood dynamics at the catchment scale. A source-to-impact flood analysis was performed to identify locations characterised by the highest flood hazard and locations that contribute the most to this hazard. This information was then used to derive a set of potential criteria to guide spatial prioritization for flood management intervention. In what follows, the results are discussed and specifically applied to illustrate how the combination of different criteria can guide spatial prioritization for BGI. Furthermore, the experimental focus of the study needs to be stressed, which means further research into various aspects of the approach will be needed to develop a standardised approach. Therefore, methodological considerations and areas for future research and improvement are also discussed.

4.1 Spatial prioritization for flood management intervention

The analysis presented in this study illustrates that a single type of data (i.e. difference maps, Figure 4) can provide multiple interpretations in terms of spatial prioritization for flood management. In fact, this observation is symptomatic of flood management, which is often strongly context specific and depending on a wide range of factors.

When Criterion 1 (flood extent) and 2 (max depth) are considered, catchment-scale flood dynamics can be identified, which have implications for where to install flood management measures. As expected from an upstream catchment, the cells in the upper part generally contribute the most to the total flood extent (Figure 5) while they are characterised by relatively low levels of flood hazard locally (Figure 3). In comparison, the middle part of the catchment generally has cells with high flood hazard caused by the cells in the upstream catchment. However, flooding can also be generated more locally, which is illustrated in the lower part of the catchment, where cells are characterised by high flood hazard and a high local contribution in terms of flood depths (Figure 5a-b). Based on these results, the upper part of the catchment is the logical location to install measures to retain as much surface water as possible, while localised measurements are also required to address the deeper flooding in the lower part of the catchment.

However, when also considering criteria related to the impact of the flood source areas on infrastructure systems (Criterion 3 and 4), the resulting analysis provides an alternative spatial prioritization. For example, when considering exposure and potential damages to the transport network, the cells in the upper part of the catchment can be considered as areas of lower priority for intervention, because these cells mostly cause surface flooding in greenspace (Figure 5c), while the cells with a high priority for flood management shift towards the eastern and middle part of the catchment (cells causing flooding on road network and high exposure) (Figure 5-6).

The findings illustrate the importance of considering the catchment holistically and identify spatial connectivity between locations to manage flooding and associated potential impacts on different infrastructure systems. Furthermore, the fact that the selected criterion can be combined and interpreted in different ways stresses the importance of setting objectives related to the flood management (Almoradie et al., 2015; Othman et al., 2014). This is further illustrated in the next section for BGI.

4.2 Prioritization for BGI

In the rainfall cell dependency analysis, rainfall input was entirely removed in each cell. While this is generally not representative for most flood management measures, BGI assets can approach this conceptual idea as they are often designed to retain as much water as possible (e.g. retention basin, green roofs) (City of New York, 2017; Gregoire and Clausen, 2011; Rotterdam Climate Initiative, 2018). Areas (i.e. cells) with a high proportion of greenspace that contribute significantly to the total flood extent, therefore, offer clear opportunities to promote management interventions that use this greenspace to retain the generated runoff.

Following the combination of Criterion1, 3a and 4 (Section 3.4), priority areas for using existing green spaces to retain water are situated in the upper to west part of the study area (Figure 7).

These priority locations generally correspond well with where the hypothetical BGI was placed by Morgan and Fenner (2017) and the urban development sites of Newcastle Helix (Figure 1). It has to be emphasized that these investigation and actual plans for Newcastle are the result of intensive research and collaboration between a range of stakeholders (O'Donnell et al., 2017b). Therefore, the presented approach is especially useful as a starting point for stakeholder collaboration and spatial prioritization prior to developing actual flood alleviation schemes.

4.3 Methodological considerations and future research

This study presented a transferable way to systematically assess the connection between locations with a high flood hazard and source areas. It demonstrates how combining this information with land use information can provide a holistic view to help guide a more integrated approach to flood and water management at the city scale.

It needs to be stressed that mapping and combining different criteria as proposed in this study does not provide specific types of flood management intervention. It is aimed at providing the basis for a high-level screening tool to target specific priority locations, which can then become the subject of a more in-depth investigation or the starting point for multi-agency flood planning. Furthermore, in further development of the methodology, this information can be combined with tools and techniques that identify locations with the highest need for BGI in terms of additional benefits such as air and water quality improvements, increasing access to green space, reducing social vulnerability to natural hazard and landscape connectivity (Meerow and Newell, 2017).

In developing this approach further, some methodological considerations must be acknowledged. First, it is recognized that capturing all the rainfall in a single location (cell) is not realistic. Second, the only event simulated in this study was of a one-hour duration. The duration of the event is likely to influence the result (e.g. in longer events water can flow further downstream and antecedent moisture conditions can cause different response times). Further research should therefore focus on investigating the impact of varying amounts of rainfall being captured as well as the timing of events. Third, the cell dependency analysis was performed using a regular grid. To be better linked to the actual study area, the analysis could also be based on terrain-based sub-catchments or potentially even administrative boundaries to take into account an additional level of complexity related to cross-boundary management. Finally, to improve the accuracy of the modelling results, CityCAT simulations could also be run taking into account the sub-surface drainage network (Bertsch et al., 2017).

5. Conclusion

This study innovatively applied a hydrodynamic flood model to link flood hazard information with flood source dynamics, which was used to define potential spatial priority criteria for flood management intervention. Different criteria lead to different spatial prioritization information, which stresses the importance of combining criteria that address the specific needs and targets of flood management plans. One of the key outcomes of this research is that the approach can be especially useful as a starting point for stakeholder collaboration and spatial prioritization prior to developing actual flood alleviation schemes. In doing so, the approach will help identify opportunities to combine multiple urban systems and allocate resources more efficiently.

To date, the proposed criteria remain experimental, but this paper demonstrates that this type of analysis has the potential to be developed into a framework to assess flood dynamics within the urban catchment systematically and to provide a transferable and comparable way to prioritize and identify flood management strategies from a catchment perspective.

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