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FLOOD DAMAGE ASSESSMENT FOR URBAN GROWTH SCENARIOS

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ABSTRACT

A GIS-based tool was developed, using the hazard information obtained from hydraulic modelling, building parcels, and depth-damage curves, to evaluate the damage caused by flooding. The tool was further improved in the paper so that it can utilise the land cover classes predicted by the urban growth model to estimate the flood damage in the future scenarios. New depth-damage curves for different land cover classes are established by analysing the relationships between the building layout and uses in reality, and the urban growth model prediction of cover classes for the baseline year. Apart from direct building damage, the tool can be applied to assess the impact of flooding on safety and human health. With the new depth-damage curves and the land cover classes predictions, the tool can evaluate the future flood damage to help the development and evaluation of flood resilience measures.

KEYWORDS
Climate change; damage assessment; flood resilience; urban flooding; urban growth.

1. INTRODUCTION

The European Floods Directive defines flood risk as “the combination of the probability of a flood event and of the potential adverse impacts on human health, the environment, cultural heritage and economic activity associated with a flood event” (European Commission, 2007). Several similar definitions in the literature also agree that flood risk is the probability of a certain flood event, combined with its impact (HR Wallingford, Flood Hazard Research Centre, Middlesex University and Risk & Policy Analysts Ltd., 2006). Kron (2003) regarded flood risk as relating the nature of the hazard and its probability of occurrence, to the people and assets that are potentially exposed to the hazard, and their vulnerability. When a potentially exposed population comes into a contact with a hazard, their vulnerability will determine the impacts of the hazard. Sufficient understanding of the hazard and its risk can help decision makers to adopt adequate measures for flood damage reduction (James and Hall, 1986). The effectiveness of these alternatives can be evaluated by considering the reduction of risk that proceeds from the implementations of these measures. Therefore, flood risk evaluation requires a proper understanding of the consequences and probability of flood events.

Urbanisation associated with economic growth, particularly in developing countries, has become an inevitable fact in the past half century (United Nations, 2010). Today, more than 50% of the world’s population lives in urban areas. This trend is continuing and it is estimated that nearly 70% of world population will be living in urban areas by 2050. Hazard risks and exposures increase rapidly in cities (Mitchell, 2003) as a consequence of the concentration of population and wealth, exhaustion of resources, and changing environmental and human activities.

To evaluate the impact of flooding, White (1945) considered different aspects of flood impacts: (1) damage to physical property; (2) interruption of business and services; (3) loss or impairment of human life; and (4) reoccupying and rehabilitating. Many following studies adopted the concept and re-termed them as combinations of tangible, intangible, direct and indirect damage. A tangible damage is a damage that is capable of being assessed in monetary terms (Smith and Ward, 1998). Similarly, Messner et al. (2007) defined a tangible damage as one that can be “easily quantified in monetary terms”. Intangible impacts are those, in contrast, which cannot be so easily quantified. Tangible damage includes the cost of physical damage to property, or the loss of business due to interruptions in the economy during and following a flood event. Intangible damage might include the loss of human life, or the increased burden of disease.

For direct tangible damage, White related the land use types to the depth-damage functions to evaluate the property damage (White, 1964), which has become the standard approach in flood modelling studies (Smith, 1994). These functions relate the characteristics of the floodwaters to the damage that is caused. These functions are usually applied as a relationship between the flooded depth and damage, although there are studies where other characteristics such as flooded duration and flow velocities are considered (McBean et al., 1988). Therefore, multiple DDCs are often built corresponding to different land use types. Smith (1994) and Dutta et al. (2003) estimated the flood damage using the hazard map with the Depth-Damage Curves (DDCs). In earlier application, the lack of high resolution data often restricted the damage evaluation in a broad scale such as land use zoning in a city.

The DDCs can be developed through empirical approach, using historical data to develop the relationship between the inundation characteristics and damage. The empirical approach has been used in multiple studies and relies on the existence of reliable historical flood damage data. Examples of such studies include work in Brazil (Nascimento et al., 2007) which used a reference flood event from 2000, work in Japan (Dutta, Herath and Musiakec, 2003), or the work in Germany (Merz et al., 2004). If such empirical data exists, it should be used, even if in conjunction with a synthetic approach. Such damage data can be collected either from official agencies, or from insurance companies.

The other approach is synthetic such as the UK's Multi-coloured Manual (Penning-Orwsell et al., 2010), where expertise was used to build a database of absolute damage curves for over 100 building types. The synthetic approach does not mean that it is artificial (Messner et al., 2007), the creation of the damage curves often involves the synthesis of all data, including historical data. Some authors have differed slightly on the meaning of this term. Merz et al. (2007) have described this approach as being developed by applying "what-if" scenarios, and argued that the synthetic approach and the empirical approach can be combined, whereas Penning-Rowsell would see this as a synthetic approach, with the empirical and synthetic approaches being mutually exclusive.

The advance of the GIS information and the computing power has enabled the accessibility of detailed spatial data and modelling results. Hénonin (2007) developed a toolbox in the ArcGIS to identify the buildings which had its edge(s) within a buffer distance to flooded areas, obtained from the hydraulic modelling results of the DHI MIKE Flood. Hence, the total number of affected buildings can be counted for further evaluation of the flooding damage. Alexander et al. (2011) developed a GIS tool using Visual Basic on the ESRI ArcMap that can demonstrate various information, including hazard, vulnerability, financial losses and risk to life. Two hazard models were applied to assess the damage: (1) Risk to Life: classified based on the combination of flood depth and velocity (Priest et al. 2008); (2) Flood damage: based on the depth-damage functions from the Multi-Coloured Manual (Penning-Orwsell et al., 2010). Although there is much literature that has discussed flood damage calculation, very few studies propose methodologies that can be applied to different case studies, and different data types and structures efficiently. Meanwhile, some approaches combine the land use regions and the average flood depth to evaluate the damage. We would argue the suitability since the DDCs are non-linear such that the average could lead to inaccurate estimation.

In the CORFU project, we aim to develop a framework for flood damage assessment that can be applied to different Asian and European cities. The flood damage includes (1) direct tangible damage; (2) indirect tangible damage; and (3) intangible damage. Within the framework, we developed common tools to assess various types of flood damage in different cities. Considering the dissimilar data availability of our case studies, the flexibility of data requirement was the main concern when we developed the tools. In this paper, we would like to focus on the detailed technical issues for creating the CORFU damage assessment tools and the problems we have encountered during the development.

2. METHODOLOGY

2.1 Development environment

As an integrated project framework, and most of the CORFU case studies have built hydraulic models using DHI MIKE software (MIKE Urban, MIKE 21 and MIKE 21 FM), we developed a series of tools using Python scripts and the Geoprocessing functions within the ESRI ArcGIS software. The tools allow the minimum manual input to calculate the flood damage based on the hydraulic modelling results and other supplementary information. Most other GIS software platforms provide similar functions with their own syntax and support integration with Python. The Python scripts can be easily adapted by changing the Geoprocessing functions to the corresponding functions in other GIS software platforms. With the detailed explanation of the algorithms, any modeller who uses other GIS software packages/platforms can easily implement the same functions. We aimed to make the best use of available information, so the tools are capable of dealing with fine resolution data and will aggregate the information into coarser scales when needed.

Some algorithms applied herein are difficult or inefficient to implement under the GIS environment, hence, separate executable programs were developed to provide those functions. The standard GIS data format is adopted as the inputs and the outputs of the standalone executable programs so the data can be easily imported or exported in GIS software.

2.2 Flood damage assessment for current reality

For direct flood damage assessment, we assumed that the damage is related to the use of a building so that each building polygon must contain use information, which can be associated to a damage function for calculation. For the cases of building with multiple uses, the components of various uses can be used and the damage will be calculated according to the area ratio of different uses. If the building layer does not include any usage information, overlapping with the land use zoning data will associate a building with a particular land use depending on its location. The locations and layouts of objects (buildings, vulnerable groups) are essential to determining damage at the parcel level based on their spatial relationship with hazards. All these information can be obtained from field surveys or statistic reports, and should be able to represent the current reality properly. Each object needs a unique index so that the damage to individual objects can be counted. When parcel information is absent, the direct application of the zoning data is also a possible option in the CORFU damage tool. But the zoning data may include the non-parcel areas, and the applicability will depend on the definition of DDCs.

The relationship between hazard and vulnerability provides the link to calculate damage. Table 1 shows the hazard-vulnerability functions required for evaluating various types of damage. Direct tangible damage assessment includes the residential properties, non-residential properties, technical infrastructure, vehicles and cars, and agricultural damage (Messner et al., 2007). A DDC is used to represent the flood damage of a specific land use type based on the flood depth. For the case that flood duration is taken into account, more than one DDC could be applied to the same land use type. In this study, the residential and non-residential property damage are merged as building content damage, assuming that the depth-damage curves (DDCs) are available for both types of properties. The damage to vehicles can be reflected in the DDCs or assessed separately, depending on the condition of a case study. The individual tool for assessing vehicle damage will be developed later. Technical infrastructure such as transportation networks and flood defences will also require a separate model for their assessment. Agricultural products are excluded from the study.

The same model can also be used for assessing the health impacts. The assessment of health impacts at the parcel level may not be available (neither appropriate), and it would therefore be more sensible to look at the block or district level. Using demographic information to build up Contamination-Health Impact Curves or Depth Mortality Curves for each block or district, the health impact can be evaluated with the same tool.

Table 1 Flooding damage types and required hazard and vulnerability information for assessment

Damage	Hazard information	Vulnerability
Building content/construction damage	Flood depth (and duration)	Financial loss
Building construction damage	Flood velocity (and duration)	Building resistance
Pedestrian safety	Flood depth	Human physical resistance
Pedestrian safety	Flood velocity	Human physical resistance
Driving safety	Flood depth	Vehicle resistance
Driving safety	Flood velocity	Vehicle resistance
Human body health	Contamination concentration (and duration)	Human body resistance

2.3 Flood damage assessment for urban growth scenario

In the CORFU project, an urban growth model (UGM) has been developed (Veerbeek and Zevenbergen, 2013) to project future changes in land cover, based on historic land use and land cover (LULC) change data. The UGM also considers different drivers such as alternative growth rates, growth containment and zoning plans to predict the possible future scenarios. However, the UGM only provide the classification of land cover, which represents the density of built-up areas and does not directly correspond to a specific land use. Meanwhile, detailed information on building parcels is unavailable from the UGM. The above-mentioned approach using building layout and DDCs per building use are not suitable for such situation. The flood damage would be assessed using land cover classes and new DDCs have to be developed for those classes.

The development density of a region is related to the area and the use of buildings within its extent. Therefore, the analysis of building components of each land cover class can provide the weights of different building uses to determine the new DDC for a land cover class. For the baseline year, both the building reality information and the land cover classes are available, and the comparison of these two dataset can establish the relationship between them. Assuming the future land cover classes from the UGM have the same building components to the ones in the baseline. the new DDCs can be applied to assess the flood damage in the future.

2.4 Modelling tool

The proposed tool can take 2D hydraulic modelling results from both regular grid, such as those are used in the MIKE21, or irregular mesh, such as the output from or MIKE 21 FM and Infoworks 2D, from 2D hydraulic modelling results as inputs. For a given combination of rainfall, boundary, and terrain conditions, a hydraulic model normally produces detailed information of flooding after a simulation, including: (1) maximum flood depth; (2) maximum velocity; (3) maximum contamination; and (4) snapshots of flood depth, velocity, and contamination at selected timings; which form the base for direct damage assessment.

The spatial information could be either in vector (polygon, polyline or point) or raster formats. The parcel objects and the zoning data are often in polygon format. Both irregular mesh (polygons) and regular grids are commonly used in hydraulic modelling. In this study, the outputs from MIKE 21 are in raster format, and the outputs from MIKE21FM can be converted to raster format as well, which allows the data to be processed directly in the ArcGIS environment.

The vector and the raster data cannot be compared directly for analysis. For example, when the bare DEM is used for hydraulic modelling, a building polygon may contain more than one grid cell. Selecting the representative value to describe the flood depth of a building would be difficult because the non-linearity of damage curves. Therefore, the format conversion step is applied to ensure that data are compared in the same format. The raster format is often used to represent data values which change rapidly spatially. The conversion from raster to vector formats would result in a large number of vectors, which would be a less efficient format for both data storage and processing. Therefore, when the input data include both vector and raster formats, the CORFU tool will automatically convert vector to raster for data processing. It also allows the reverse conversion from raster to vector when the analysis is finished.

By overlapping the hazard information, vulnerability for a parcel or a zoning area, and the hazard-vulnerability functions, the damage/health impact per unit area is then calculated. Although the ArcGIS has a function of look-up tables, it can only be used to retrieve the value from the given sampling points. The hazard information such as flood depth is unlikely to be the same as the ones have been defined in the look-up tables, interpolation is necessary to determine the value between two sampling points. Therefore, an external program is developed for the purpose.

In the case that a parcel or zoning polygon includes multiple vulnerability groups (e.g. mixed-use buildings, or different age groups in an area), the components of the various factors will affect the damage calculation. The combination of factors may vary from building to building such that it would be difficult to define the DDC for each building. To simplify the input, the DDCs per unit area are used together with the ratios of different factors at a location to estimate the total and the components of damage.

3. APPLICATION AND DISCUSSIONS

In this paper, we adopted Dhaka in Bangladesh as the case study. Greater Dhaka includes areas beyond Dhaka City Corporation which extends over an area of 259 km^2. It is bounded by the Balu River in the east, the Tongi Khal on the north, the Turag-Buriganga Rivers on the west and the Dhaka-Demra-Chittagong Road cum embankment on the south. The average population density in central Dhaka city is 48,000 inhabitants per km^2. With rapid urbanisation and development of city infrastructure, combined with the reduction of water storage and percolation areas, flooding and water logging from local rainfall has reached a dangerous magnitude. Details about the hydrology and hydraulic environment of the case study can be found in a separate paper (Khan et al., 2013).

The Institute of Water Modelling (IWM), Bangladesh, provided the detailed parcel information that contains more than 110,000 buildings in Dhaka. Figure 1 shows the current, i.e. the baseline year, building layouts and uses in a local region. Most buildings are for residential use, followed by manufacturing and processing activity, mixed use and commercial activity. The IWM adopted the DDCs from the UK's Multi-coloured Manual and developed DDCs of six main building use types in Dhaka.

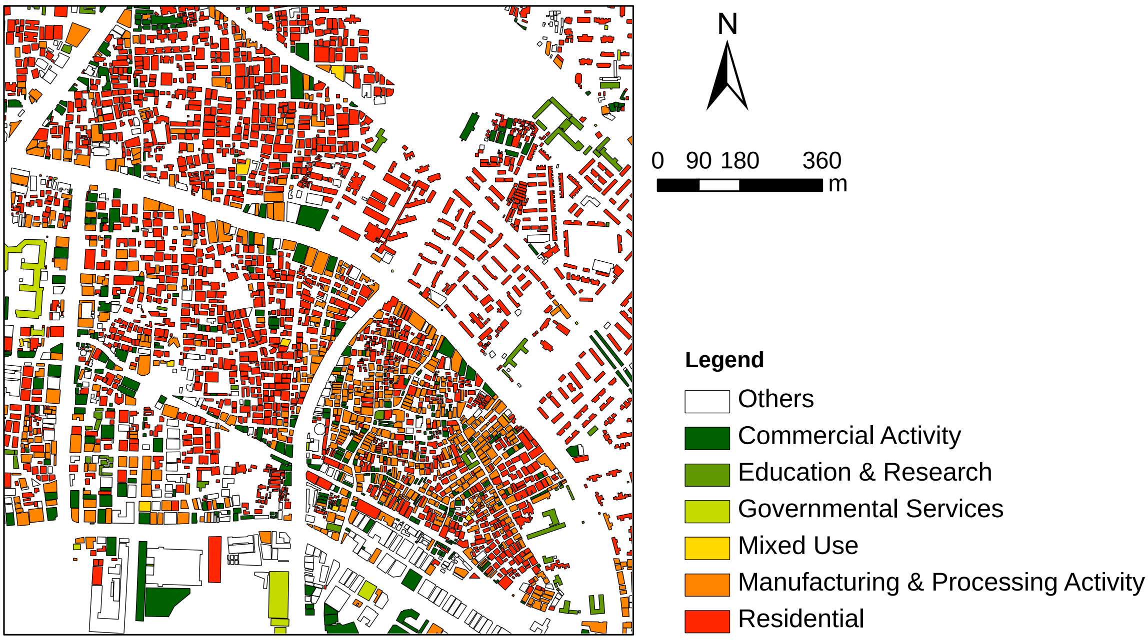

Figure 1 The building layouts and land use types in a local region in Dhaka for the baseline year

Figure 2 shows the land cover classes in the same area for the baseline year, predicted by the UGM using historical data. The higher class number (darker colour) represents more dense development. Comparing to Figure 1, the northeast part of the region has sparser building distribution such that the land cover classes in Figure 2 are lower in the area. We further analysed the detailed relationship between building use and land cover. Table 2 shows the building components of each land use cover. The total built-up area of these six main categories for the land cover varies from 3.8% (class 1) to 64.5% (class 10). We used these area ratios of building components as the weighting factor to combine DDCs of different building uses and generated new DDCs for each land cover class.

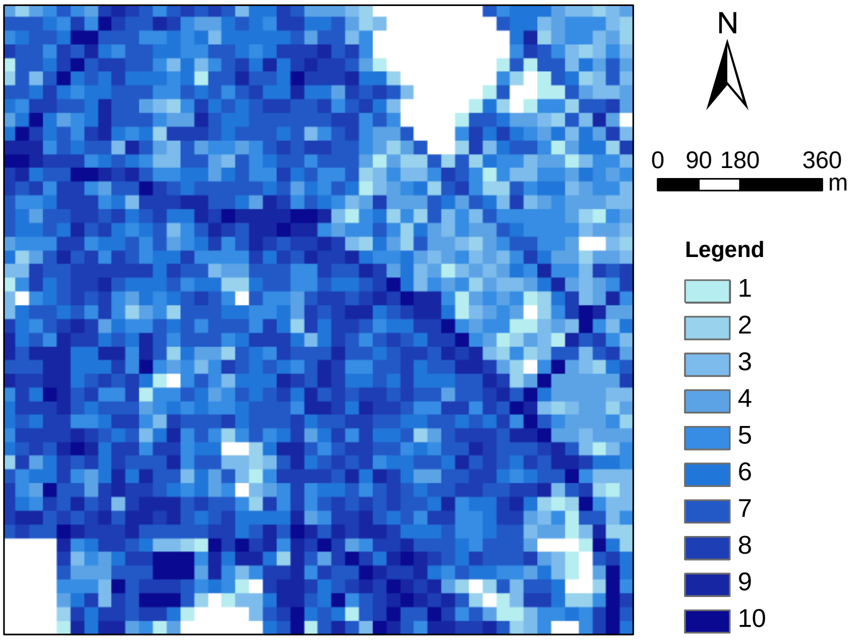

Figure 2 The land cover classes for area shown in Figure 1 for the baseline year predicted by UGM using historical data

Table 2 The building components for different land use classes

Land cover class	Building use					
	Comm. Activity	Edu. & Resear.	Gove. Services	Mixed Use	Manuf. & Proc. Activity	Residential
1	0.1%	0.0%	0.0%	0.0%	0.0%	3.7%
2	0.4%	0.2%	0.0%	0.2%	0.1%	10.3%
3	0.9%	0.5%	0.1%	0.6%	0.3%	16.6%
4	1.6%	0.7%	0.1%	1.3%	0.7%	21.4%
5	2.4%	0.8%	0.2%	2.0%	1.4%	26.5%
6	3.2%	0.9%	0.2%	2.7%	2.7%	31.5%
7	4.1%	0.8%	0.2%	3.6%	4.5%	33.9%
8	6.3%	0.8%	0.3%	5.9%	7.4%	30.8%
9	9.8%	0.9%	0.5%	12.6%	8.4%	21.4%
10	11.0%	1.2%	0.5%	36.4%	2.8%	12.6%

Using the DDCs that the IWM developed for Dhaka building uses, and the derived DDCs for land cover classes, the flood damage for a 100 year event is estimated as shown in Figures 3 and 4. Figure 3 illustrates the flood damage for each building in the region of a flood event for current reality, while

Figure 4 represents the flood damage per unit area using the land cover classes for the same event and the same baseline year. There is no parcel information available in the UGM prediction such that the damage cannot be integrated into building level.

Meanwhile, the land cover classes can be replaced using different information such as population density, so that the same tool can be applied to assess the flood impacts on human health for the baseline and the future scenarios.

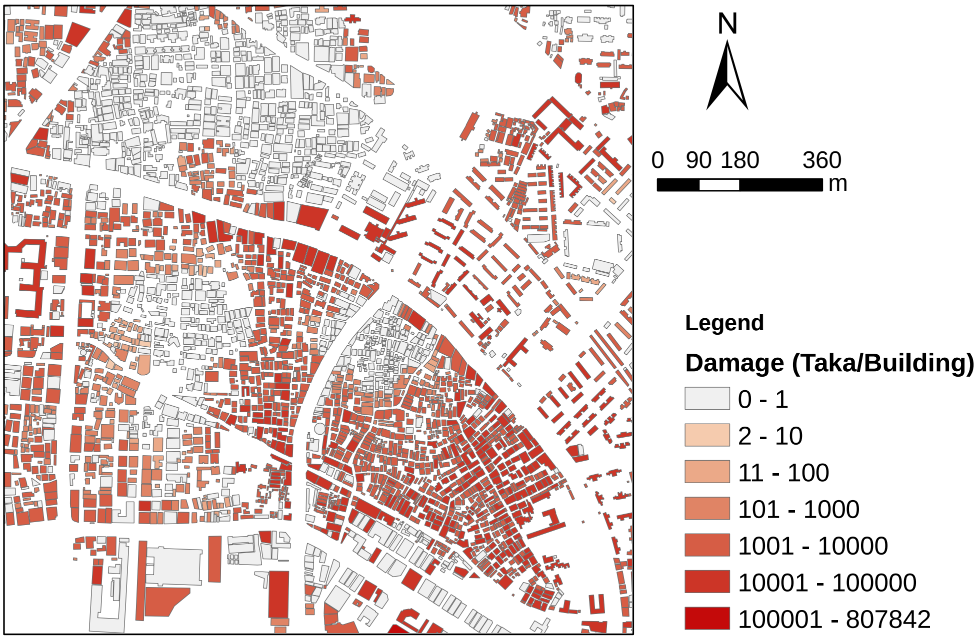

Figure 3 The flood damage per building estimated using the parcel information reality in the baseline year

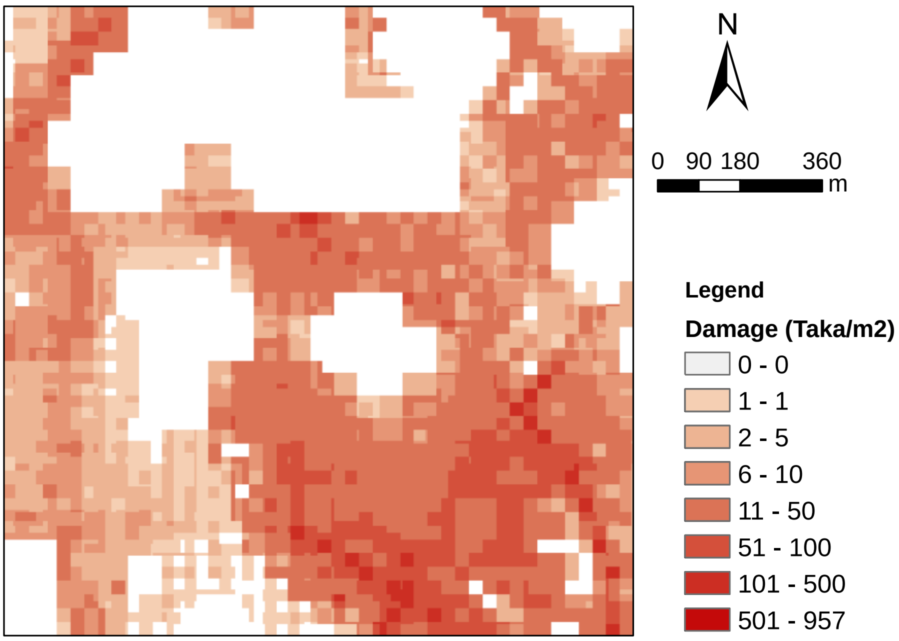

Figure 4 The flood damage per unit area using the land cover classes prediction from the UGM for the baseline year

However, the assessment can be summarised at the city level for the total damage in each building use or each land cover class, as listed in Table 3 and Table 4, respectively. For Dhaka city as a whole, the approach using land cover classes overestimated the total damage by 29% compared to the former approach.

Table 3 Total flood damage for 100yr return period event estimated with the current building reality information for the baseline year

Building use type	Damage (Taka)
Comm. Activity	12,040,169
Edu. & Resear.	4,252,463
Gove. Services	2,127,335
Mixed Use	50,866,730
Manuf. & Proc. Activity	21,459,496
Residential	274,146,783
Total	364,892,977

Table 4 Total flood damage for 100yr return period event estimated with the land cover classes for the baseline year

Land cover class	Damage (Taka)
1	16,275,510
2	31,128,656
3	36,006,832
4	44,958,480
5	67,149,808
6	80,172,592
7	96,679,056
8	57,518,344
9	27,212,650
10	15,109,972
Total	472,211,900

For the future, Figure 5 shows the land cover classes in 2050s for the business-as-usual (BAU) high growth scenario predicted by the UGM. Although the region is already highly developed in the baseline year, the projection shows that the density of development will increase. Consequently, the flood damage for the same 100 year event will be more severe, as shown in Figure 6.

The assessment using the land cover classes shows 29% overestimation, compared to the results obtained using the parcel information, for the 100 year event in the baseline year. This could be due to the relationships between the building use and the land cover was not good enough to associate the current reality to the conceptual classes. This could be improved by introducing more factors when analysing such information. For example, the change of built-up areas and building uses due to urban growth in developed area and in undeveloped area could be different due to the spatial limitation; the commercial activities tend to grow along the road network due to the accessibility of business. Therefore, more detailed relationships between building use and land cover classes should be developed to improve the flood damage assessment.

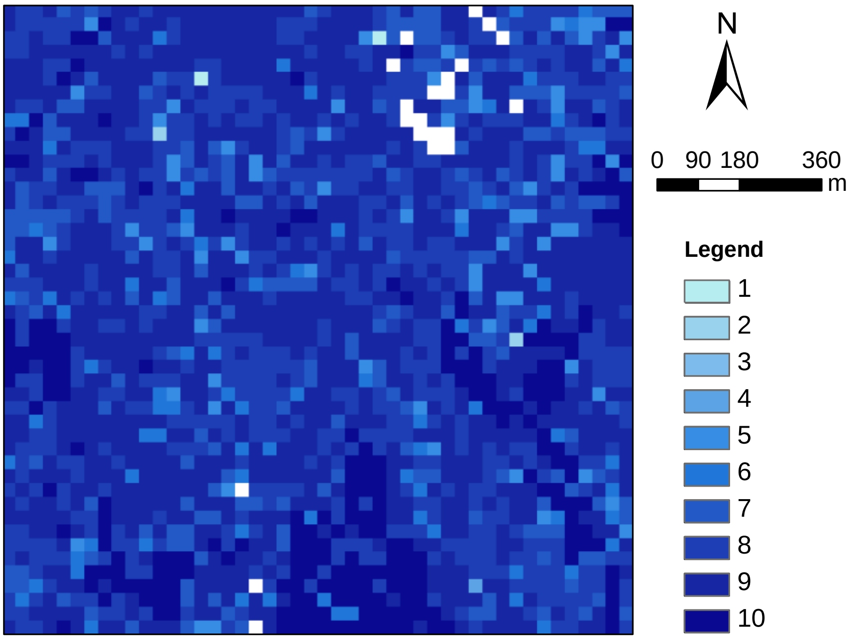

Figure 5 The land cover classes for the BAU high growth 2050s scenario predicted by UGM

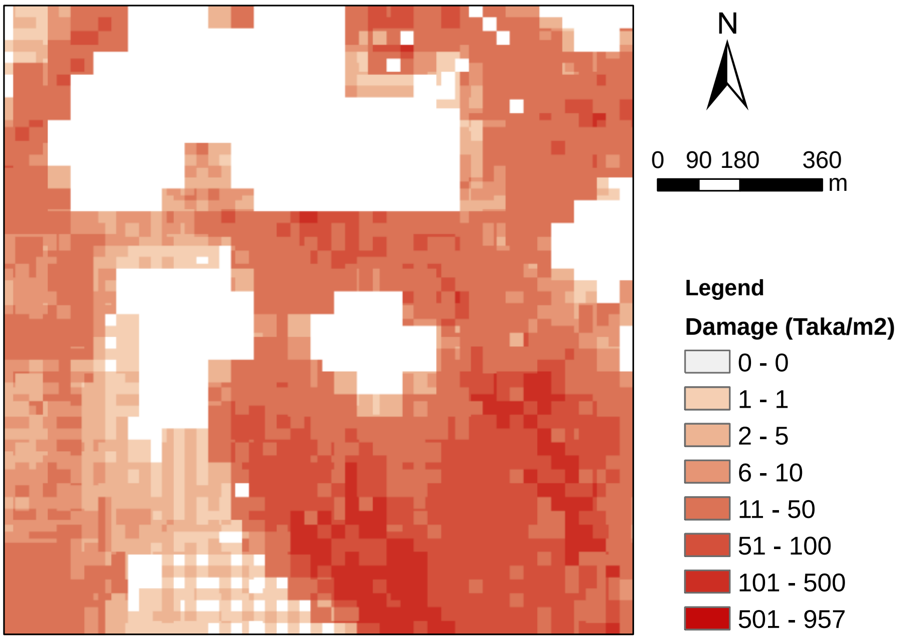

Figure 6 The flood damage per unit area using the land cover classes of the BAU high growth scenario in 2050s predicted by UGM

4. CONCLUSION

In this study, we established a GIS-based tool for flood damage assessment. The tool is capable utilising the hydraulic modelling results from the DHI MIKE URBAN directly. Combining the building uses and their corresponding DDCs, the tool can evaluate the flood damage efficiently. We have also proposed an approach to associate the land use classes projected by UGM to the current reality for the baseline year. Therefore, the tool can be further applied to assess the future flooding damage using the data from the UGM.

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