Spatial modelling of adaptation strategies for urban built infrastructures exposed to flood hazards

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Keywords: Flood risk, adaptation/coping capacity index, adaptation/coping strategies, fuzzy logic, geographical information system (GIS), LIDAR

Abstract

The recent 2010/2011 floods in the central and southern Queensland (Australia) prompted this research to investigate the application of geographical information system (GIS) and remote sensing in modelling the current flood risk, adaptation/coping capacity, and adaptation strategies. Identified Brisbane City as the study area, the study aimed to develop a new approach of formulating adaptation/coping strategies that will aid in addressing flood risk management issues of an urban area with intensive residential and commercial uses. Fuzzy logic was the spatial analytical tool used in the integration of flood risk components (hazard, vulnerability, and exposure) and in the generation of flood risk and adaptation capacity indices. The research shows that 875 ha, 566 ha, and 828 ha were described as areas with relatively low, relatively moderate, and relatively high risk to flooding. Identified adaptation strategies for areas classified as having relatively low (RL), relatively moderate (RM), relatively high (RH), and likely very high (LVH) adaptation/coping capacity were mitigation to recovery phases, mitigation to response phases, mitigation to preparedness phases, and mitigation phase, respectively. Integrating the results from the flood risk assessment, quantitative description of adaptation capacity, and identification of adaptation strategies, a new analytical technique identified as flood risk-adaptation capacity index-adaptation strategies (FRACIAS) linkage model was developed for this study.

1 Introduction

Flood hazards are the most common and destructive of all natural hazards (Vanneuville *et al.,* 2011) and flood damages had been estimated to be the most costly in Australia (BTRE, 2002 and Geoscience Australia, 2010). With the recent 2010/2011 floods and the destruction wrought by Severe Tropical Cyclone Yasi in the central and southern Queensland, the Queensland Government had declared the State being disaster-affected (QRA, 2011). Left with devastated infrastructures, and the tragic death of 37 people, the event prompted to rebuild the State amounting to $6.8 billion (QRA, 2011). In 1974, the floods in South East Queensland (SEQ) region caused damages in Brisbane alone costing approximately $700 million at 1998 values (Middelmann, 2002). Between 1967 and 1999, the Bureau of Transport Economics (BTE) estimated that the direct average annual cost of floods in Australia was $315 million, with 99 deaths and 1019 sustained serious injuries (Middelmann, 2002).

To reduce the impact of flooding, flood hazard mapping has been considered a vital component for appropriate land use planning in flood prone areas (Linham and Nicholls, 2010). In doing so, flood forecasts are usually determined by examining past occurrences of flooding events, determining recurrence intervals of historical events (known as Annual Recurrence Interval), and then extrapolating to future probabilities (known as Average Exceedance Probability) (Baer 2008). These modelling and mapping techniques produce a better understanding of the causes and magnitude of disastrous flooding and provide flood information necessary to support development of an integrated strategy to improve disaster resilience and preparedness in the flood hazard reduction areas (Teasdale *et al*., 2010). However, the main drawbacks of models are that they are seldom perfect descriptions of nature (Stedinger and Crainiceanu, 2001) or inherently inexact (Quay and Frangos, 2010). For examples, the January 2011 flood waters reached a height of reduced level being 0.85m higher than the Q100 flood level published prior to January 2011 (Arnold, 2011). On the operation of the Somerset and Wivenhoe Dams during the same event, the Bureau of Meteorology (BoM) emphasised that the provision of accurate and reliable forecasts of rainfall amounts and intensities is currently limited by the state of meteorological science and modelling (Baddiley, 2011).

The risk of flooding in SEQ region is also exacerbated by the absence of state-wide flood management regulations (Middelmann, 2002). In Queensland, the Local Government Authorities (LGAs) have been left with the responsibilities of implementing flood disaster risk reduction schemes. However, despite stringent development guidelines were in place, the 2010/2011 floods are manifestations that flooding remains problematic in the SEQ region. Population growth, low flood hazard awareness (Middleman, 2002), flood concept confusion and misunderstanding from a large proportion of stakeholders (Holmes and Dinicola, 2010; Godber, 2005), low employment rate and other socio-economic disadvantages have also increased people's, infrastructure's, and community's risk to flooding.

Given the limitations of flood risk management policies and the sciences involved, a matter of priority and urgency requiring consideration is to improve community resilience. One of the alternatives would be to build a stronger adaptation measures and strategies to prepare the community from the destructive nature of natural hazards. With the scale and scope of the weather events which affected Queensland in 2010/2011, local government authorities need to plan, build stronger and more resilient communities (QRA, 2011). Also, the Councils need better information to make informed decisions about how and where to build (QRA, 2011). Spatial modelling of adaptation strategies was one of the options explored in this study.

2 Objectives of the Study

This study aims to apply spatial science (specifically, GIS and remote sensing) in developing a new approach of formulating adaptation strategies to improve resiliency of an urban area from floods by utilising high resolution spatial data inputs.

Specifically, the objectives of this study are the following:

1. To assess data inputs and spatial analytical technique/s in generating a current flood risk map of an urban area with intensive residential and commercial uses; and
2. To generate a spatial-based adaptation/coping capacity index and corresponding adaptation/coping strategies that will aid in addressing flood risk management issues of an urban area.

3 The Study Area

The study area is located in the core district of Brisbane City, the Queensland's capital in Australia. The City is traversed by the 345-kilometer long Brisbane River, which is the longest river in South East Queensland and flows down from Mount Stanley to Moreton Bay (Middelman, 2002). Including the Lockyer Creek and Bremer River catchments, around 6,500 km^2 (approximately 50%) of the Brisbane River catchment is below Wivenhoe and Somerset Dams (Robinson, 2011). Completed in 1984, the Wivenhoe Dam was built as a dual-purpose storage for both drinking water (which supplies water to the City) and flood mitigation (SEQ Water, 2009).

In a report prepared by the Brisbane City Council (BCC) (2011), the City has been described as Australia's New World City. With strong economic growth, the City has an $85 billion economy, almost half of the State economy. However, the Brisbane's economic progress together with more than a million estimated residents, had been hampered and devastated recently by 2010/2011 floods. In January 2011, the Brisbane River broke its banks and inundated the city in the biggest floods to hit Queensland's capital since 1974 (Queensland Museum, 2011). Flood waters in Brisbane peaked at 4.46 metres making it one of the worst floods in the city's recorded history (Queensland Museum, 2011). Significant damage to transport, infrastructure, residential properties, as well as earth's excavation of a section of South Bank has made the January flood the most destructive natural disaster experienced by the city (Queensland Museum, 2011). Out of the 29,000 homes and businesses affected by inundation in SEQ (Queensland Floods Commission of Inquiry, 2012), an estimated 18,000 of these properties were came from Brisbane and Ipswich (IBIS World, 2011).

Comprising an area of about 2,200 ha, the study area includes the suburbs of South Brisbane, West End, Highgate Hill, Brisbane Central Business District (CBD), Toowong, Auchenflower, and portions of Spring Hill, Paddington, Bardon, St. Lucia, and Dutton Park (Figure 1). On the South Brisbane side, the area is home to major cultural attractions and art galleries, Australia's only beach in a city, Brisbane's best restaurants and cafes, and one of the East Queensland's most popular tourist destinations. Aside from offering tourism services to an estimated 10 million people each year, the area is devoted to several land uses such as recreation parks, commerce and business, industry, education, residential, cultural centres and museum, State Library of Queensland, among others (South Bank Corporation, 2012). Within the CBD, the centre takes the role of the Queensland's principal vicinity for business and administration complemented by retailing, entertainment, education, community and cultural facilities, tourism and residences (BCC, 2010).

The study area is also part of the Brisbane City Council's (BCC) Long Term Infrastructure Plan (BLTIP) 2012-2031 and the City Centre Neighbourhood Plan. The former identifies actions to deliver eight infrastructure strategies for transport, water, energy, telecommunications, waste management, social infrastructure, green space, and key districts (e.g. Greater Central Business District) (BCC, 2012). On the other hand, the latter is a specific local plan that envisions the City Centre as a compact with high density buildings and as Queensland's principal Centre for business and administration, among others (BCC, 2009). At this stage of the study, the built forms of the study area's infrastructure system (i.e. residential and commercial areas) were examined rather than specific infrastructures.

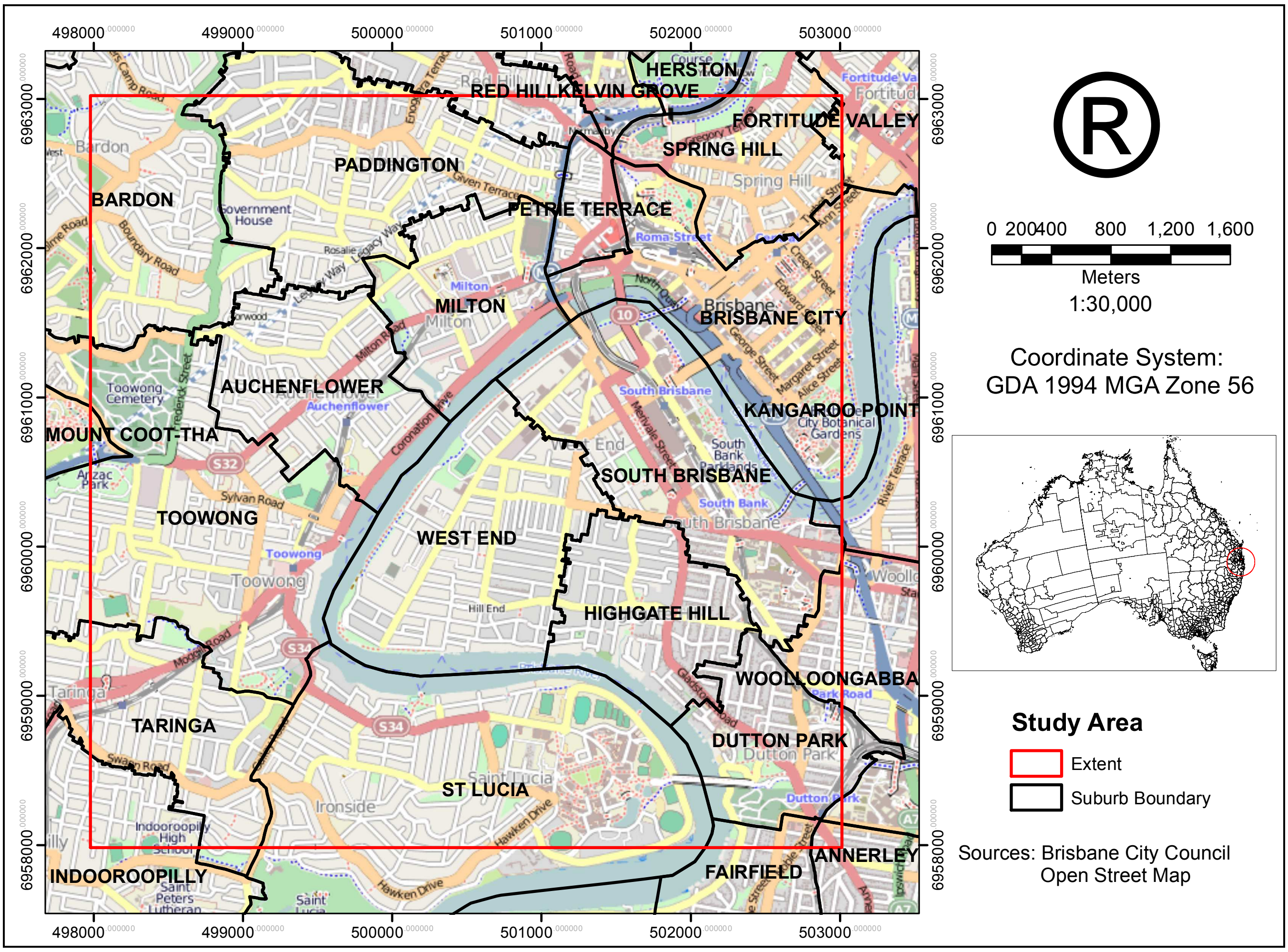

Figure 1. Map and extent of the study area

The concern of dealing with this approach can be associated with the implementation of Neighbourhood Plan. This Plan envisions the City Centre, for example, as a compact City with a built form characterised by high rise office and residential towers wherein car parking is located underground and the lowest levels of new developments are occupied by retail, commercial or community uses (BCC, 2009). While the purpose of this developmental design is noble, which is to provide activities close to the public domain (BCC, 2009), it is important to examine that part of these developments will be placed in a flood-prone area.

4 Research Method

This paper is part of a larger research project which attempts to apply spatial science (specifically, GIS and remote sensing) in developing an integrated approach of formulating adaptation strategies to reduce vulnerability of an urban area and infrastructure assets from floods and the long-term effects of climate change. Shown below is the diagram of the input-process-output (IPO) model which presents the flowchart of the study (Figure 2). Highlighted in the figure are data inputs, processes involved, and the outputs which relate to existing flood risk, the main focus of this study. Under the input component, the flood hazard, vulnerability, and exposure indicators were assessed with corresponding details and assumptions enumerated in Table 1. These data inputs were then standardised, analysed and processed using applicable GIS operations with emphasis on fuzzy logic operations of ArcGIS 10. This procedure in turn produced initial outputs representing flood risk component index maps (i.e. hazard, vulnerability, and exposure index maps). Out of these analytical and processing operations, existing flood risk index map, adaptation/coping capacity index map, and adaptation strategies map were generated.

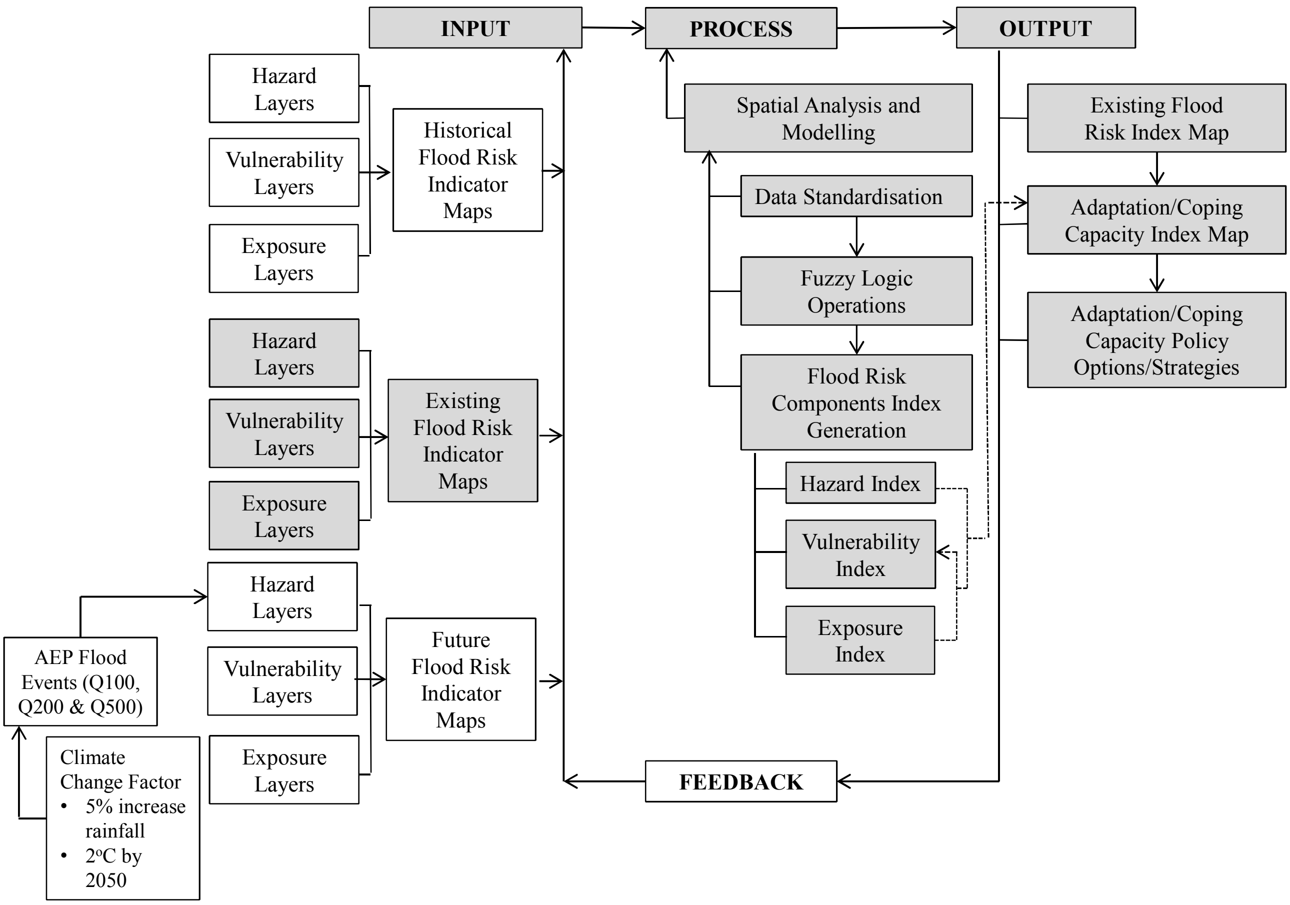

Figure 2. The Input-Process-Output Model used in the study

Flood risk assessment methods are generally designed to characterise and understand the system's degree of risk to flood (e.g. low, moderate, high, and extreme). In GIS, this is called descriptive modelling, which refers to the characterisation of the direct interactions of systems components to gain insight and understand the system processes (Berry, 1995). It is very seldom that prescriptive modelling is applied in flood disaster risk reduction and mapping adaptation strategies in response both to flood and climate change risks. By definition, prescriptive modelling refers to the characterisation of direct and indirect factors related to system response used in determining decision and appropriate management action (Berry 1995). This study attempts to contribute a new knowledge by developing spatial analytical technique/s in generating both descriptive map representing adaptation capacity index and prescriptive map representing adaptation policies and strategies for flood risk management.

5 Flood Risk Assessment and Modelling

a. Key Concepts and Data Inputs

The United Nations International Strategy for Disaster Reduction (UNISDR) (2009) defined *risk assessment* as a "methodology to determine the nature and extent of risk by analysing potential hazards and evaluating existing conditions of vulnerability that together could potentially harm exposed people, property, services, livelihoods and the environment on which they depend". As shown in Figure 2, this study dealt with *existing risk* that refers to "the risk a community is exposed to as a result of its location on flood plain and applies to existing buildings and development" (Mirfenderesk and Corkill 2009). This paper also considers the *outcome risk* instead of *event risk* wherein the former refers to the risk of a particular outcome and integrates both the social or inherent vulnerability and the chance of the occurrence of an event that jointly results in losses while the latter refers to the risk of occurrence of any particular hazard or extreme event (Brooks 2003;). Mathematically, risk can be expressed in these forms (Mirfenderesk and Corkill 2009; Hughey and Bell 2010):

Risk = Hazard x Vulnerability x Exposure　　　Eq. 1

Risk = Hazard + Vulnerability – Adaptive Capacity　　　Eq. 2

As shown in the above equations, the terms hazard, vulnerability, exposure, and adaptation/coping capacity are significantly associated with the risk concept.

The UNISDR (2009) defined *hazard* as a "dangerous phenomenon, substance, human activity or condition that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage". Brooks (2003) referred the term *hazard* as "the physical manifestations of climatic variability or change, such as droughts, floods, storms, episodes of heavy rainfall, long-term changes in the mean values of climatic variables, potential future shifts in climatic regimes". For this study, spatial datasets associated with the flood hazard are the January 2011 flood extent, flood level/elevation, and digital elevation model (DEM) generated from high resolution 2009 LIDAR data.

Geoscience Australia (2010) conceptualised *vulnerability* as "the impact a hazard has on the people, infrastructure, and the economy". For this study, the term *vulnerability* has been introduced to consider the extent to which people suffer from calamities which depend on the likelihood of being exposed to hazards and their capacity to withstand them, which relates to their socio-economic circumstances (Schneiderbauer and Ehrlich, 2004) rather than a response to the hazard-centric perception of disaster (Schneiderbauer and Ehrlich, 2004). By analogy, according to Kelly and Adger (2000), the existent state of the system determines the vulnerability of any individual or social grouping and their capacity to respond to a hazard.

Considered in this study are spatially explicit proxy datasets for vulnerability per suburb taken from the Brisbane City Community Profile and prepared by the Australian Bureau of Statistics (ABS) and Office of the Economic and Statistical Research (OESR), Queensland Treasury and Trade (QTT). These include the 2006 Index of Relative Socio-Economic Disadvantage (SEIFA), type of residential tenure, household income quartiles, 2008-2009 total counts of registered businesses with turnover, 12-month (ending 31 March 2012) total building (residential and non-residential) value, and estimated period of settlement particularly during the significant growth in residential, industrial and commercial activities (about 1800s-2011). Estimated average of home and contents insurance per suburb was also used and generated from the Suncorp Insurance's Postcode Profiler accessed in July 2012.

E*xposure* is defined as the number of assets such as "people, property, systems or other elements present in hazard zones that are thereby subject to potential losses" (UNISDR 2009). For the purpose of this study*, infrastructure assets* are defined as "systems and services as interrelated built, institutional and environmental systems and services" (Jollands *et al.,* 2006). Exposed infrastructure assets with relevance in this paper are the built forms specifically the residential and commercial areas. Spatial datasets such as 2010 estimated residential population, 2006-2011 average annual population growth rate, 1999 land use, 2006 residential density per suburb, and the number of January 2011 flooded residential and commercial properties per suburb were considered in the exposure analysis.

Finally, the term *adaptive capacity* has been viewed as a system response to perturbations or stress that are sufficient to make fundamental changes in the system itself, shifting the system to a new state or how the system responds (Gallopin, 2006; Preston and Stafford-Smith, 2009); hence, may also be referred to as *response capacity* (Preston and Stafford-Smith 2009). Attempts were made to quantify and spatially represent adaptive capacity, termed as *adaptive capacity index*, like the works of Advanced Terrestrial Ecosystem Analysis and Modelling (ATEAM) in Europe and the Victorian Climate Change Adaptation Program, Department of Primary Industries in Victoria, Australia. The former was a generic vulnerability-focused adaptive capacity index while the latter is an industry-based (i.e. dairy) participatory adaptive capacity assessment at a local and regional scale (Fitzimons *et al.,* 2010). This study, on the other hand, attempts to apply Eq. 2 in quantifying adaptive capacity, such that by mathematical transformation, adaptive capacity index (ACI) can be expressed as follows:

$$\text{ACI} = \text{Vulnerability} - (\text{Risk} + \text{Hazard}) \qquad \text{Eq. 3}$$

Table 1 summarises the list of spatial datasets used to analyse each risk component. Described in the Table are the assumptions used in processing data inputs and generating outputs.

Table 1. List of hazard, vulnerability, and exposure datasets

Risk Component	Spatial Dataset	Assumption	Source
Hazard	2011 Flood Extent and Flood Height (m)	River flood that spills into the residential and commercial areas shows the actual extent of flood hazard.	DERM and QGIS; Pers. Comm. A/Prof. K. McDougall, USQ
	2009 Digital Elevation Model (m)	Generated from 2009 LIDAR points, flooded elevation indicates flood hazard of the area. The lower DEM values indicate relatively highly flooded areas.	DERM and Pers. Comm. A/Prof. K. McDougall, USQ
Vulnerability	2006 SEIFA Index	SEIFA indicates the degree of disadvantage of an area of few families of low income, people with little training, and unskilled occupation. The higher the index value, the less disadvantaged the area is compared to other areas.	BCC and ABS
	2006 Residential Tenure – Renting (%)	Dwellings being rented are less likely to be maintained than dwellings that are owned and being purchased; hence, vulnerability to flood damage is likely high.	BCC and ABS
	2006 Household Income Quartiles – Household with Highest Income Group (%)	Group with the highest distribution of household income (e.g. annual income of $88,210 and over) is less likely vulnerable than the lower income groups.	BCC and ABS
	2008-2009 Total Counts of Registered Businesses with Turnover (No.)	Suburbs with higher counts of business with turnover indicate higher revenue and less vulnerable than suburbs with lower counts.	OESR, QTT
	2012 Total Building Value ($'000)	Suburbs with the highest recorded building values are less vulnerable than other suburbs.	OESR, QTT
	2012 Insurance (Home and Content) ($)	Areas with higher average sum of insurance are more likely flood-prone areas and more vulnerable than other suburbs.	Suncorp Insurance
	Estimated Period of Settlement (Year) – Period of significant growth of residential, industrial and commercial activities (1800 -	Areas earlier settled and with significant growth in residential, industrial and commercial activities have more likely older buildings than other areas; hence, relatively more vulnerable from wear-and-tear and require higher investment for retrofitting, maintenance and	BCC, ABS and Centre for the Government of Queensland

Risk Component	Spatial Dataset	Assumption	Source
	2011)	improvements.	
Exposure	2010 Estimated Residential Population (No.) and 2006-2011 Annual Population Growth Rate (%)	An area with higher number of estimated residential population or annual growth rate puts likely more pressure on the use of and expansion of residential and commercial areas and likely highly exposed to flood hazard.	OESR, QTT
	2006 Residential Density - (High Density) (%)	Areas with higher percentage of high density type dwelling structure (i.e. flats and apartments in 3-storey and larger blocks) are less likely exposed to flood hazard than areas of higher percentage with separate and medium density type of houses.	BCC and ABS
	2011 Flooded Residential and Commercial Properties (No.)	Suburbs with higher number of flooded residential and commercial properties during the January 2011 floods are more likely exposed to flood hazard than other suburbs.	Houghton, *et al.*, 2011

Note: All datasets from BCC and ABS were taken from "enumerated" category which was counted on 08 August 2006. Values on the period of settlement are not directly taken from the sources but a mere interpretation of the texts. Number of flooded residential and commercial properties was taken at peak flood height 4:00 a.m. 13 January 2011.

b. Data Processing and Analysis

In this work, the common procedures used in processing datasets include the generation of available datasets from secondary sources, adding fields (i.e. vulnerability and exposure proxies/indicators) to attribute tables of suburb boundary, and performed other overlay operations. These vector datasets were rasterised into 5m grid, and then the values were standardised from the original values into 0 to 1 using the ArcGIS 10 Fuzzy Logic Toolbox.

Fuzzy logic was used as the analytical tool to treat the above assumptions (see Table 1) as a matter of degree. Introduced by Zadeh in 1965, fuzzy set theory embraces the membership function (or the values False and True) to operate over the range of real numbers (0, 1), reflecting the degree of certainty of membership (Brule, 1985; Pradhan, 2011). In GIS-based natural hazard mapping, the idea of using fuzzy logic is to consider the spatial objects on a map (e.g. areas on an evidence map) as members of a set (e.g. areas hazardous to landslide) wherein the unconstrained (subjective judgment) fuzzy membership values must lie in the range 0 and 1 rather than being measured over discrete intervals (Pradhan, 2011). As a tool to handle complex problems such as flood risk assessment, fuzzy logic is attractive because it is straightforward to understand and implement, allows flexibility of combining maps, could be readily implemented with GIS language (Pradhan, 2011), and manipulates spatial objects of different measurement units into standardised values.

c. Hazard Index

The 2011 flood extent was used to clip the flood height model (FHM) of the study area to determine the minimum and maximum raster values of flood. The clipped FHM raster was then overlaid on top of the study area's Digital Elevation Model (DEM) to assess the maximum raster elevation value (MREV) that has been flooded. The DEM had been initially derived from high resolution 2009 LIDAR points using ArcGIS 10. The derived MREV (approximately 12 meters AHD) was used in the operation of the Fuzzy Linear Membership Type to model flooded and non-flooded pixels such that pixels with equal and below these values are flooded rasters and assign Fuzzy Membership Values (FMV) of 0 and above these values are greater than 0 to 1. The FMVs above 0 are non-flooded areas and as the FMV closes to 1, the hazard becomes relatively lower. These values, however, were further "re-fuzzified" to re-assign pixel values with 0 as 1 (highly flooded areas) to conform to the GIS norms and easy understanding. The result of the analysis was the hazard index.

d. Vulnerability Index

As enumerated in Table 1, both physical and socio-economic sets of proxies/indicators were used in this study. Guided by the assumptions specified in Table 1, FMVs were generated to assess the degree of vulnerability (e.g. as the pixel FM values close to 1 using the SEIFA index, the pixels are described as relatively more vulnerable being highly disadvantaged in the original pixel values). Depending on how these proxies/indicators relate to vulnerability, the Fuzzy Membership Type (FMT) varies (e.g. Fuzzy Large and Small). With the previous SEIFA Index example, the Small FMT was used such that smaller original pixel values were assigned with higher fuzzy membership values in the function to indicate highly disadvantaged index. Similar analysis was engaged with the other proxies/indicators.

After all these proxies/indicators had been standardised into FMVs, results were then combined to generate the vulnerability index of the study area using the Fuzzy "AND" Overlay Operations of ArcGIS 10. This type of fuzzy logic operation was performed to identify pixels of common social and biophysical resources/strengths. In other words, these pixel values reflect the "common wealth" of the area being studied. The result of the analysis was the vulnerability index.

e. Exposure Index

In other risk equation, like when hazard has been treated as probability of occurrence, the exposure component could be taken out from the exercise (e.g. other equation cited by Hughey and Bell 2010). In this study, population, annual population growth rate, per cent of high residential density type of dwelling structures, and number of flooded commercial and residential properties during the January 2011 flood were treated under this component. Similar with vulnerability datasets, exposure proxies/indicators had been standardised with Fuzzy Logic; however, the exposure index was generated using the Fuzzy "OR" Overlay Operations of ArcGIS 10. Logic prompts the operation of this type in fuzzy to identify the maximum pixel values that would reflect the areas that were highly exposed to flood damage.

Prior to the fuzzification process, the analysis for the number of properties flooded was different from other proxies/indicators. This dataset was combined with the 1999 land use to assign the number of residential and commercial properties flooded within the respective residential and commercial land uses per suburb.

6 Results and Discussions

a. Flood Risk

Having settled the fuzzy parameters, variables, and logic operations, the flood risk index was calculated. Applying Eq. 1, the product of the pixel values from the hazard index, vulnerability index, and exposure index were calculated using the Fuzzy "PRODUCT" Overlay Operation of ArcGIS 10. However, the use of fuzzy algebraic product produces a "decreasive" effect such that the flood risk index output is controlled by the fuzzy multiplier or fuzzy multiplicand; it is either smaller or equal to these fuzzy values. To resolve this problem, the Fuzzy "GAMMA" Overlay Operation had been opted to. The Fuzzy GAMMA operator combines the "increasive" effect of Fuzzy "SUM" Overlay Operation and the "decreasive" effect of the Fuzzy "PRODUCT" Overlay Operation (Farrell, et al., 2006). This means that operating Eq. 1 in fuzzy logic renders a limitation such that this equation could be expressed not just a mere "product" operation but could be extended to a "gamma" operation.

Figure 3 shows the areas with relatively low, relatively moderate, and relatively high risk to flooding cover 875 ha, 566 ha, and 827 ha of the study area, respectively. Table 2 summarises the result of the analysis.

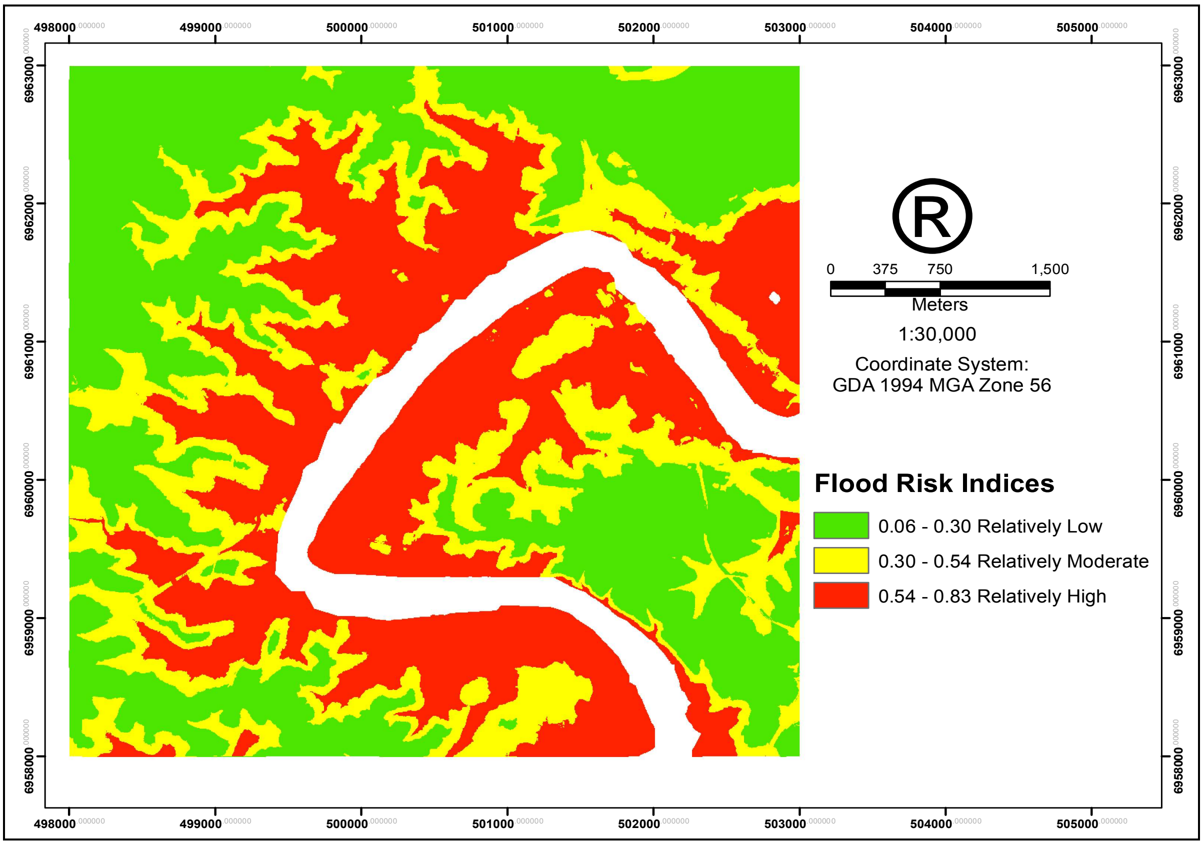

Figure 3. Flood risk map of the study area

Table 2. Descriptive and quantitative flood risk of the study area

Flood Risk Index	Description	Area (ha)	%
0.06 – 0.30	Relatively low	875	39
0.30 – 0.54	Relatively moderate	566	25
0.54 – 0.83	Relatively high	828	36
Total		2269	100

b. Adaptation/Coping Capacity

The results of the creation of the adaptation/coping capacity index (ACI) were taken from the flood risk mapping exercise discussed above while adaptation strategies were taken from existing literature. In generating the ACI, several assumptions were made. The vulnerability index had been recalculated to include the exposure proxies/indicators and viewed these proxies/indicators as part of the vulnerability proxies/indicators. This was done to address from being biased such that when the flood risk index was calculated, exposure proxies/indicators were part of the exercise; however, it was taken out in Eq. 3. This integration is a valid implementation of Adger's (2006) contention. Adger (2006) identified two of various commonalities in vulnerability research: 1) vulnerability does not exist in isolation from the wider political economy of resource use; and 2) vulnerability has been constituted to include exposure and sensitivity to perturbations or external stresses, and the capacity to adapt.

Figure 4 is the result of implementing Eq. 3. The result of the analysis shows that 611 ha and 714 ha of the study area has relatively low and likely very high adaptation/coping capacity, respectively. Quantitatively, the indices were indicated in negative values and made this study more interesting to further deliberate as how the adaptation/coping capacity components (risk, hazard and vulnerability) are intrinsically inseparable. For example, if vulnerability in this study takes its definition as the capacity of the people, community, or system to withstand risk and/or hazard, it follows then that vulnerability is inherently associated with the general political-economy of resources, wealth, physical and social well-being, governance, and political will (among others). This significant finding would imply that vulnerability as a "resource"-oriented factor determines the strength or weakness of the area of interest; such that generated ACI with negative values meant that the resources are not enough to increase resiliency of the built infrastructures (e.g. commercial and residential areas). Table 3 summarises the quantitative adaptation/coping capacity of the study area.

Looking at Figure 4, however, the above theory does not necessarily mean that when areas have negative ACI values are automatically meant to be non-adaptive areas. It should be interpreted to be meant to be less adaptive areas comparable to the neighbouring areas and across the geographic area of interest.

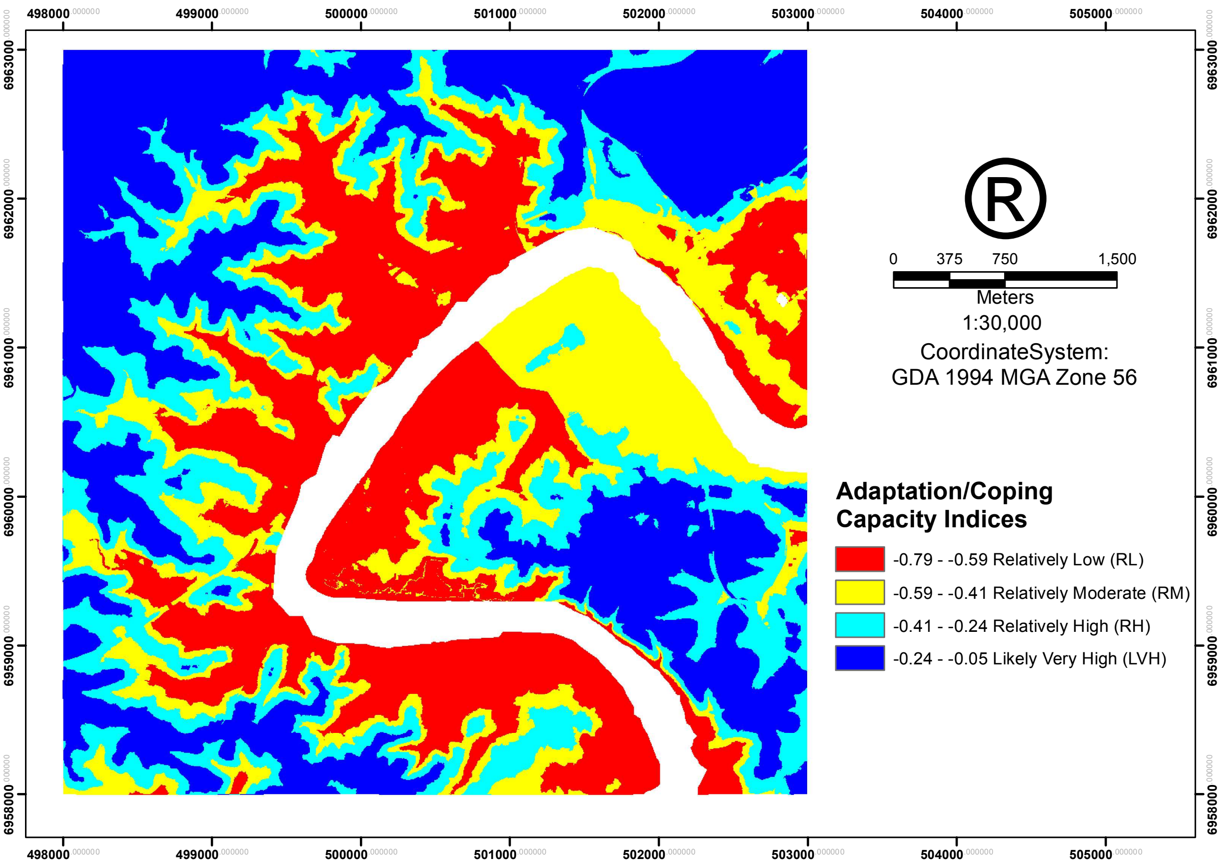

Figure 4. Adaptation/coping capacity index model of the study area

Table 3. Descriptive and quantitative ACI and corresponding adaptation strategies of the study area

ACI	Description	Area (ha)	%	Adaptation/Coping Strategy
-0.79 - -0.59	Relatively low (RL)	611	27	Mitigation to Recovery
-0.59 - -0.41	Relatively moderate (RM)	461	20	Mitigation to Response
-0.41 - -0.24	Relatively high (RH)	482	21	Mitigation to Preparedness
-0.24 - -0.05	Likely very high (LVH)	714	31	Mitigation
Total		2269	100	

Taking the information from Figure 4 and Table 3, corresponding adaptation/coping strategies were identified as shown in Figure 5. The Queensland Reconstruction Authority (QRA) (2011), for example, adopts the four phases of disaster risk reduction: mitigation, preparedness, response, and recovery. Inferred from Table 3 and Figure 5, for areas with relatively low adaptation/coping capacity, the corresponding adaptation/coping strategies are proposed to include the entire phases; that are from mitigation to recovery. On the other hand, for areas with likely very high adaptation/coping capacity index, the mitigation phase is the optimum strategy; hence, in effect allocating limited resources effectively. These findings could be linked with the Agriculture and Resource Management Council of Australia and New Zealand's (ARMCANZ) suggested design for urban infrastructures located in floodplain areas. ARMCANZ (2000) recommends that the design of urban infrastructures should minimise the effects of flooding and consider flood response mechanisms during the onset of the flood, evacuation operations, flood plain management, including clean-up until recovery phases.

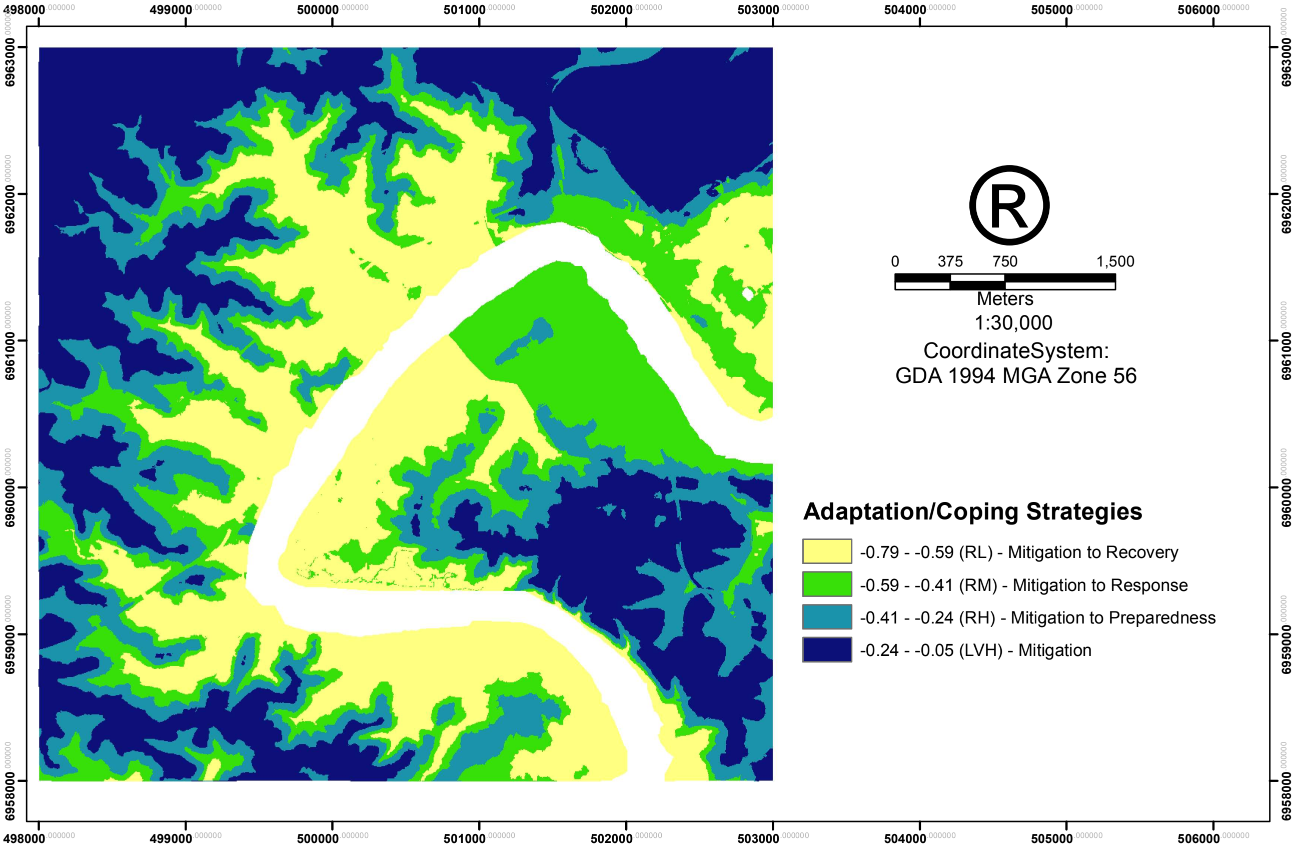

Figure 5. Adaptation/coping strategies model of the study area

Inferred from Figure 5 is the significant association of adaptation/coping capacity index and adaptation strategies based on initial flood risk assessment. The former quantitatively describes how the human system responds to the actual extreme climatic event (i.e. flood) given the available resources and physical/natural conditions. On the other hand, the latter prescribes what are the strategic possibilities or options, either in general or specific sense, that would aid to reduce disaster risk across the geographic area of interest. Briefly, prescription or management action to reduce flood risk requires a systematic description, either qualitative or quantitative, of the system under examination; hence, interestingly they become inseparable components in flood risk management. Conversely, adaptation strategies are likewise significant components in flood disaster risk reduction. Figure 5 is a result of an operational example how flood risk assessment, quantitative description of adaptation capacity, and corresponding adaptation strategies can be linked together.

This flood risk-adaptation capacity index-adaptation strategy (FRACIAS) linkage model can also be expanded to support the current idea of linking climate change adaptation (CCA) and disaster risk reduction (DRR) frameworks. Treated these separately over the past years as having different views and concepts, emphasis in the recent years had been placed on the integration and coordination of these two concepts (Joshi, et al., 2011). This study had examined the detailed application of this attempt to integrate and reduce the gaps between the CCA and DRR frameworks as briefly explained above.

7 Conclusions and Recommendations

This study had examined a new approach of developing spatial analytical technique/s in generating both descriptive map representing adaptation/coping capacity index and prescriptive map representing adaptation policies and strategies for flood risk management. In achieving these results, flood risk assessment had played a significant input all throughout the process. Hence, this output does not intend to replace the existing and successfully in-placed methods but rather augment of what has been done and advance the application of Geographic Information System (GIS) and remote sensing in the flood disaster risk reduction objective. Fuzzy logic as a tool in solving complex flood problems had demonstrated significant modelling capability in generating flood risk index, adaptation/coping capacity index and corresponding adaptation strategies. Through this study, the fuzzification process standardises various spatial flood risk components (layer inputs) with different units of measurement and logically combines them through the fuzzy overlay operations of varying options. These operations also allow greater flexibility in quantifying adaptation capacity expressed in truth values that range in degree between 0 and 1. Conversely, the new analytical technique examined in this study allows the integration of the methods involved in flood risk assessment, quantitative description of adaptation/coping capacity, and adaptation/coping strategies identified as flood risk-adaptation capacity index-adaptation strategy (FRACIAS) linkage model.

By application, this exercise can be used, though general at this stage, to support the existing disaster risk reduction plans and policies prepared by any authorities, organisations, enterprises, or any sectors involved in coordinating their development plans, resource allocation, and the implementation of their respective program of activities. The strengths of the Neighbourhood Plan of the Brisbane City Council, for example, are well-noted taking into consideration of being highly specific in terms of the programs and activities and "greening" the built infrastructures to facilitate linkage to climate change plans and programs. However, noteworthy to consider as well are the weaknesses of the Plan such that, as earlier mentioned, the lowest levels of the high density buildings are proposed to be devoted for retail, commercial, and community uses and the underground for car parking. This has been the usual practice which could make the City and the newly developed areas also exposed to flood hazards; similar to what had happened in the January 2011 floods. With the ARMCANZ (2000) recommended design for urban infrastructures to consider best practice principles for floodplain management, this exercise is sensible in this instance.

Considering that this study did not cover the entire nature and extent of flood risk and that modelling of adaptation strategies are in a general sense, the following future works are recommended:

1. Inclusion of other hydrologic/hydraulic components in analysing flood hazards (e.g. observed and forecast rainfall, annual exceedance probability, flood velocity, Wivenhoe dam operation, etc.);
2. Specific evaluation of biophysical and socio-economic vulnerability conditions of the study area (e.g. DCDB-based or locational building values and building heights);

3. Identification of specific infrastructure assets like electricity, water, transportation, communication, and community services (e.g. health, education, emergency, etc.);

4. Review of the technical characteristics of climate change and how this factor could affect the flood risk assessment process;

5. Identification and field validation of specific adaptation strategies such as regulatory and maintenance and operation strategies (e.g. elevation of critical infrastructures above flood level, installation of temporary flood gates, cleaning of drainage system, sand bagging, etc.); and

6. Field validation of the generated adaptation/coping capacity and flood risk indices together with the quantity and the quality of the data inputs used.

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