Using spatial modelling to develop flood risk and climate adaptation capacity metrics for vulnerability assessments of urban community and critical water supply infrastructure

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1. Introduction

The application of vulnerability assessment in the water supply network takes into account several elements which include the characterisation of the water system, determination of critical assets, analysis of current risk (i.e. flood risk), and evaluation of existing countermeasures (EPA 2002). As a highly significant tool, vulnerability assessment of water supply network provides information to guide and prioritise plans for water supply security and mitigating measures against operational damages from destructive events such as floods.

A series of damaging floods during December 2010 to January 2011 hit the State of Queensland, in Australia. Consequently, over 200,000 people were affected (McDougall 2012), 29,000 homes and businesses were damaged and 37 people were killed (QRA 2011 and QFCI 2012). The damage was expected to cost the Australian economy triple the original estimate of AU$10 billion (ABC 2011). Specifically, in January 2011, the city of Brisbane has experienced a major flood event inundating more than 14,000 properties (McDougall 2012). The government spent almost AU$7 billion rebuilding and upgrading the State's infrastructures (QFCI 2012, QRA 2011) due to flooding.

In this study, the vulnerability of water supply infrastructure to flood hazard was examined. During the January 2011 flood, water supply was lost to few suburbs in the Brisbane local government area (QUU 2011) with Queensland Urban Utilities (QUU) provided alternative water supplies to water-deficient communities (QFCI 2011). In general, the daily drinking water requirements of Brisbane area were significantly available during the flood event; however, water supply was constrained by a major challenge caused by the interruption of water treatment operations at Mt. Crosby and North Pine dam due to water turbidity and other problems (QFCI 2011). This situation created a potentially serious water supply shortage in Brisbane not only during the January 2011 flood but was also realised during the January 2013 flood (Keller 2013). This “dirty water” event reached turbidity levels up to four times more than it was during the January 2011 flood and reduced the quality of drinking water for several days (Keller 2013, News Limited 2013).

To enquire into matters arising out of the 2010/2011 floods, the Queensland Floods Commission of Inquiry (QFCI) was established pursuant to the *Commission of Inquiry Act 1950* (QFCI 2012). Investigations and recommendations were made as to how future flood damage can be minimised across essential infrastructures such as electricity, water supply, sewerage, storm water, telecommunications, and roads and rails.

The development of flood risk and adaptation capacity metrics is of considerable importance considering the urgency and relevancy of the issues at hand. However, doing so offers a great challenge due to a wide variety of adaptations as well as the dynamic nature of various environmental and socio-economic factors (Szlafsztein 2008). This research problem is further exacerbated by inductive argumentation which particularly pertains to the sufficiency of indicating variables and availability of statistical models in climate risk assessment. Hinkel (2011) emphasised that when these indicating variables are aggregated with deductive approach (e.g. expert judgment) or by normative approach (e.g. equal weighting), the delivery of robust results is an issue due to subjective judgments in the former case and the multi-dimensionality of variables to different stakeholders in the latter case. Another challenge that further aggravates the issue is the process of selecting the indicating variables to indicate flood risk and its application to adaptation capacity assessment.

Furthermore, there is a limited research consideration on the geographical interdependency of critical infrastructure protection modelling. In a research survey of U.S. and international research on critical infrastructure interdependency modeling conducted by Pederson *et al.* (2006), modeling and simulation that provide geospatial relationships were excluded in their analysis. Because floods exert spatially correlated disturbances to water supply infrastructures and consequently disrupt water supply services to community, a research question arises as to how geographic interdependency and spatial autocorrelation operate in flood risk assessment.

To sum up, this study was conducted to address the following research questions:

1. How can indicating variables (i.e. hazard, physical and social vulnerability, and exposure) be better use in the integrated flood risk and climate adaptation capacity assessment model for assessing the vulnerability of urban community and critical water supply infrastructure?
2. Despite advances in water engineering, how can spatial technology be of help to reduce the massive flood impacts on urban community and critical water supply infrastructure and mitigate the potential spread of water-borne health problems?
3. What are the possible applications and implications of the generated modelling technique to flood insurance and land-use planning policies?

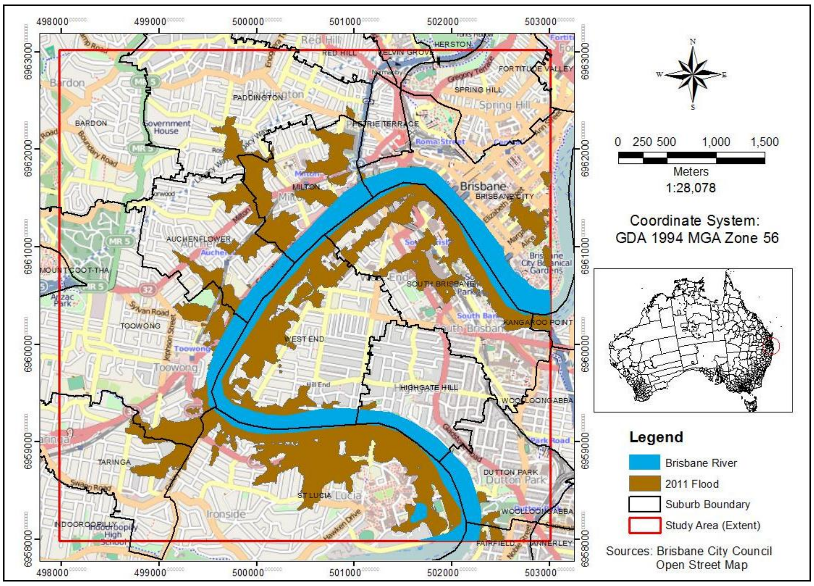
Specifically, the objectives of this study were:

1. To evaluate indicating variables in generating flood risk and climate adaptation capacity metrics of an urban area which had been exposed to flood hazard; and
2. To generate spatially-explicit flood risk and climate adaptation capacity metrics that will aid to address flood risk management and climate resiliency issues of an urban area and critical water supply infrastructure.

2. Study Area

Comprising an area of 2,200 ha, the study area is located within the 22 core suburbs of Brisbane City, the Queensland's capital in Australia (Figure 1). 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 2012).

Brisbane City had an $85 billion economy in 2011. However, the City's economic progress together with more than a million estimated residents, had been hampered and devastated recently by 2010/2011 floods. Flood waters in Brisbane peaked at 4.46 metres with significant damage to transport, infrastructure, and residential properties (Queensland Museum 2011).



Sources: Brisbane City Council
Open Street Map

Figure 1. The extent of study area

3. Research Methods

This study is part of an ongoing research project which attempts to develop an integrated approach of formulating adaptation strategies to reduce vulnerability of an urban community and infrastructure assets from floods and the long-term effects of climate change. Figure 2 is the input-process-output (IPO) model specifically used in this study.

Under the input component, the flood hazard, social and physical vulnerability, and exposure indicators were identified based on the availability of datasets and assessed following the flood risk framework. Under the process component, four main spatial analytical challenges were addressed to generate the flood risk and adaptation capacity metrics and assess water supply vulnerability: 1) transformation and standardisation of indicating variables; 2) topological cluster analysis using the self-organising neural network (SONN); 3) quantification of risk and adaptation capacity metrics; and 4) network analysis (Figure 2) (Espada *et al.* 2012, 2013).

This study was also challenged to apply the concept of geographical interdependency using the spatial autocorrelation techniques with emphasis on Global Moran's I and Cluster and Outlier Analysis of Anselin Local Moran's I. Summarising the initial outputs using the Inverse Distance Weight (IDW) method of point data interpolation, the generated raster maps were then carefully analysed to assign categorised values for each indicating variable that generally explain perceived level of flood risk.

To identify which indicating variables can be potentially included in the weighted overlay analysis, the pattern of similarity of these variables was analysed by using the self-organising neural network (SONN) mapping tool in MATLAB version R2011b program (The Mathworks, Inc. 2013). With the Bayesian joint conditional probable weights assigned to selected indicating variables, the flood risk metrics were quantified by using the modified fuzzy gamma function to resolve the mathematical issues (i.e. increasing or decreasing effects) of implementing Equations 1 and 2. Applying Equation 6, the climate adaptation capacity metrics were generated.

The final outputs (i.e. flood risk and adaptation capacity metrics) were then applied in assessing the vulnerability of urban community in general and critical water supply infrastructure in particular.

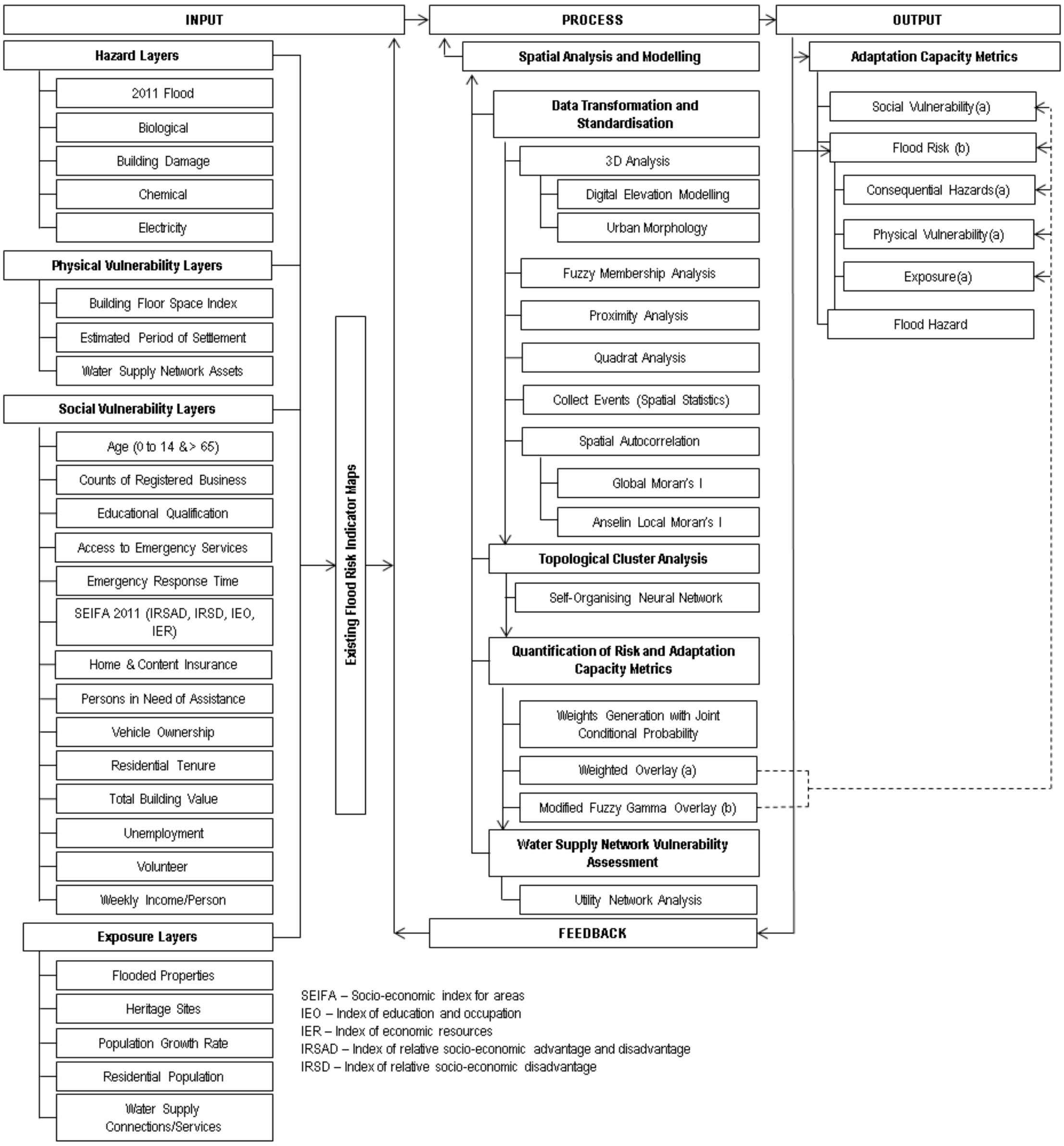


Figure 2. The input-process-output (IPO) model used in the study (Espada *et al.* 2012, 2013)

4. Flood Risk and Adaptation Capacity Modelling

4.1. Key Concepts and Data Inputs

Expressed in mathematical forms, risk can be stated as (Mirfenderesk and Corkill 2009; Downing 2002; Hughey and Bell 2010):

$$\text{Risk} = \text{Hazard} * \text{Vulnerability} * \text{Exposure} \qquad \text{Eq. 1.}$$

$$\text{Risk} = \text{Hazard} + \text{Vulnerability} \qquad \text{Eq. 2}$$

$$\text{Risk} = \text{Hazard} + \text{Vulnerability} - \text{Adaptation Capacity} \qquad \text{Eq. 3.}$$

As shown in these equations, the terms hazard, vulnerability, exposure, adaptation capacity are significantly associated to each other and can influence the flood risk assessment process.

Hazard is defined 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". From Geoscience Australia's (2010) perspective, *vulnerability* is "the impact a hazard has on the people, infrastructure, and the economy". 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). When talking about the number of assets such as "people, property, systems or other elements present in hazard zones that are thereby subject to potential losses", that is the way how *exposure* is defined by UNISDR (2009). Going further specific, the term *infrastructure assets* is described as "interrelated built, institutional and environmental systems and services" (Jollands *et al.* 2006).

Looking back to Equation 3, the term *adaptation 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). And by transforming this equation, adaptation capacity can be expressed as follows (Espada *et al.* 2012):

Adaptation Capacity (AC) = Vulnerability – (Risk + Hazard) Eq. 4

To operationalise Equation 4, it has been further expressed in Equations 5 and 6.

AC = Social Vulnerability – (Risk + Flood Hazard) Eq. 5
AC = Social Vulnerability – [(Fuzzy Gamma Function {Consequential Hazards, Physical Vulnerability, and Exposure} + Flood Hazard)] Eq. 6

Figure 2 and Table 1 show the thematic layers/indicating variables used to analyse the components of flood risk and adaptation capacity.

4.2 Topological Cluster Analysis with Self-Organising Neural Network (SONN)

This study used 30 indicating variables: 5 for hazards, 20 for vulnerability, and 5 for exposure (Figure 2). Challenged by the selection of the most appropriate indicating variables for inclusion in the flood risk and climate adaptation capacity assessments, the Artificial Neural Network (ANN) particularly the Kohonen self-organising map (KSOM) was explored in this study. A self-organising map consists of a competitive layer that allows classification of datasets with any number of dimensions into as many classes as the layer has neurons, which are arranged in a 2D topology (The Mathworks, Inc. 2011). In this study, the SOM was operationalised with the input layer where the inputs refer to the indicating variables (e.g. flood hazard, water supply assets, etc.), neuron computation, and output layer, and a map of clustered variables as shown in Figure 3 (Mele and Crowley 2008).

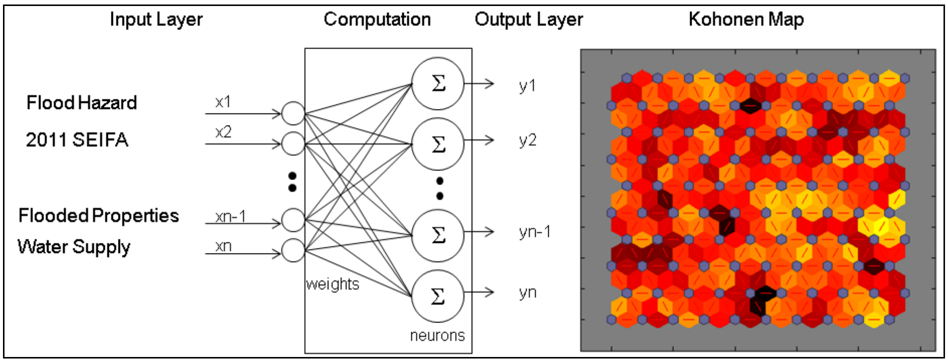


Figure 3. The conceptual self-organising neural network of the study

Processed with MATLAB version R2011b program, the indicating variables were structured to create 907266 x 5 hazard, 907266 x 20 vulnerability, and 907266 x 5 exposure matrices. Utilising the Neural Network Clustering Tool, the indicating variables were grouped or clustered by similarity through the process of classifying a 2–dimension layer of 100 neurons arranged in a 10x10 hexagonal grids. To learn the topology and distribution of indicating variables, the network was trained four times using the batch SOM algorithm with 200 epochs/iterations.

The similarity pattern of indicating variables was then analysed using the SOM planes by taking flood hazard as the basis in the pair-wise comparison. The result revealed a general pattern for two (2) variables (i.e. access to emergency services and emergency services response time) with lower weights concentrate at the centre of the SOM plane. This pattern is intuitively and visually in reverse to the general pattern showcased by flood hazard; hence these two variables were removed from further analysis.

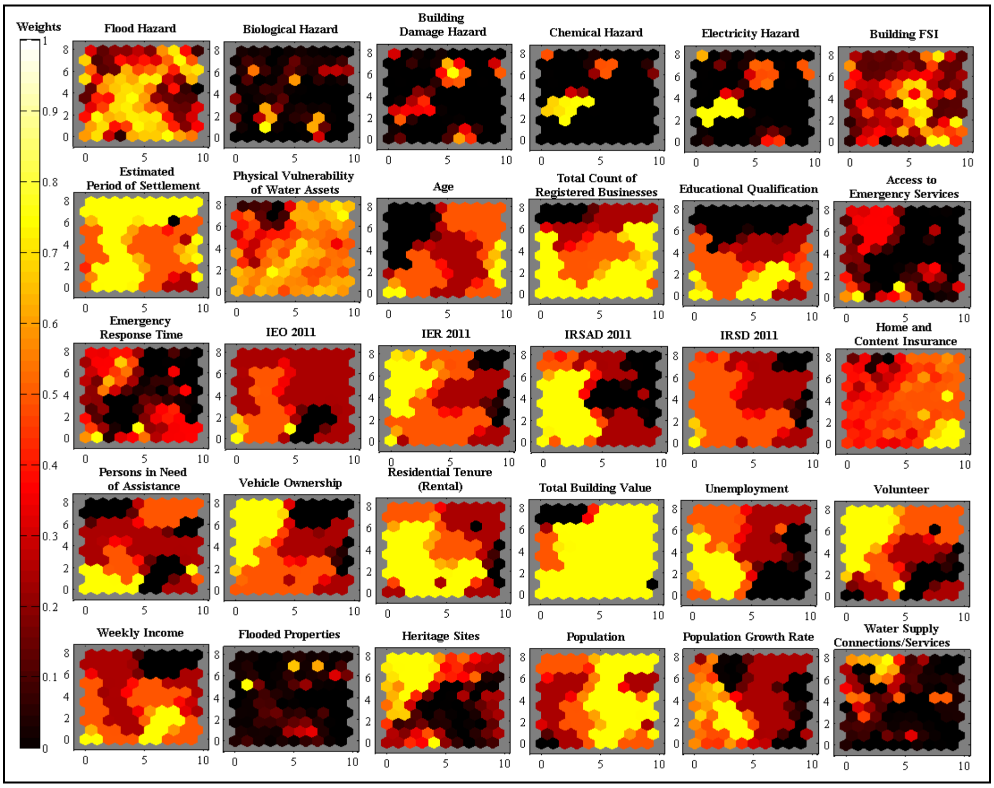


Figure 4. The SOM planes of flood risk and climate adaptation capacity indicating variables

4.3 Quantification of Flood Risk and Adaptation Capacity Metrics

From SOM analysis, the final 28 indicating variables which were selected to include in quantifying the flood risk and adaptation capacity metrics are summarised in Table 1.

The weights column from the Table indicates the unequal Bayesian joint conditional probable weight values used in aggregating the indicating variables of hazard, vulnerability, and exposure. This method of assigning weights is significant because in community vulnerability assessment, for example, people affected by floods, wetlands lost, damage cost, and adaptation cost are important dimensions to consider (Hinkel 2011), which are of unequal importance.

Using the probable weights given in Table 1, the aggregation of indicating variables for hazard, vulnerability, and exposure was performed with the weighted overlay process of Spatial Analyst Tool in ArcGIS 10. Applying Equations 1 and 6, flood risk metrics and adaptation capacity metrics were calculated with the results as summarised in Table 2 and shown in Figure 4 (map background).

Table 1. The selected indicating variables from SOM analysis and corresponding Bayesian joint conditional probable weights

Flood Risk/ Adaptation Capacity Component	Selected Indicating Variable	Joint Conditional Probable Weight
Hazard	Biological	0.19
	Building Damage	0.19
	Chemical	0.21
	Electricity	0.19
	Flood	0.22
Social Vulnerability	Age	0.07
	Educational Qualification	0.05
	Home and Content Insurance	0.08
	IEO 2011	0.07
	IER 2011	0.06
	IRSAD 2011	0.05
	IRSD 2011	0.07
	No Vehicle	0.05
	Persons in Need of Assistance	0.06
	Residential Tenure (Rental)	0.07
	Total Building Value	0.13
	Total Count of Registered Business	0.08
	Unemployment	0.05
	Volunteer	0.05
	Weekly Income	0.06
Physical Vulnerability	Building Floor Space Index	0.30
	Period of Settlement	0.31
	Water Supply Network Assets	0.39
Exposure	2011 Flooded Properties	0.31
	2011 Population	0.16
	Heritage Sites	0.12
	Population Growth Rate	0.14
	Water Supply Connections/Services	0.27

4.3.1 Applications and Implications of Flood Risk and Adaptation Capacity Metrics to Insurance and Land-use Planning

Table 2 shows that 186 ha (8%) of the study area were exposed to very high flood risk due to the January 2011 flood event. Furthermore, 221 ha (10%) were characterised of having very low climate adaptation capacity.

Also shown in Table 2, majority of the study area (90%) revealed negative adaptation capacity metrics (-31 to <0). This significant finding would imply that vulnerability as a resource-oriented factor determines the strength or weakness of the study area; such that the generated negative values for adaptation capacity meant that the resources are not enough to increase climate resiliency of the urban community and critical infrastructures (Espada *et al.* 2012). The result also signifies that the resources of the community are outbalanced by 31 units taking zero as the break-even metric. The outcome of the analysis further indicates that the capacity of the urban community requires further deliberation as how climate adaptation is intrinsically inseparable to the physical and social vulnerability of a system. If vulnerability takes the definition in this study as the capacity of the people, community, or system to withstand flood risk, it follows then that vulnerability is inherently associated with the general economy of resources, wealth, social well-being, governance, and political will of the people and community, and the capacity to increase climate resiliency of critical infrastructure assets (Espada *et al.* 2012).

Also important to further examine are the physical and socio-economic characteristics of the study area (the remaining 10%) that indicates positive adaptation capacity metrics (>0 to 1)

(Table 2). This signifies that the resources within those areas are one unit above the zero break-even or just enough to alleviate climate risk. However, extra caution should be taken into account considering that some areas are positioned in a highly favourable physical condition (e.g. higher elevation) but the socio-economic resources inhibit the adaptation to climate risk. This finding further implies that the study area requires a range of adaptation strategies that would increase community and critical infrastructure resiliency as specified in Table 1. Adopted from Queensland Reconstruction Authority's (QRA) (2011) four phases of disaster risk reduction, the broad adaptation strategies identified in this study to increase community resiliency include mitigation, preparedness, response, and recovery.

Table 2. *Summary of flood risk and adaptation capacity metrics with corresponding adaptation strategies*

Flood Risk				**Adaptation**				
Description	**Metrics**	**Area (ha)**	**%**	**Description**	**Capacity Metrics**	**Area (ha)**	**%**	**Strategy/Measure**
Low	1 – 1.02	0.6	0.03	High	0 – 0.93	218	10	Mitigation
Moderate	1.02 – 1.21	1895	84	Moderate	-1.23 – 0	1053	46	Mitigation to Preparedness
High	1.21 – 3.52	181	8	Low	-3.24 - -1.23	771	34	Mitigation to Response
Very High	3.52-30.41	186	8	Very Low	-31.41 - -3.24	221	10	Mitigation to Recovery
Total		**2263**	**100**			**2263**	**100**	

To recap, Table 2 is the summary of a methodology identified as *flood risk-adaptation capacity index-adaptation strategies* (FRACIAS) linkage model (Espada *et al.* 2012) that allows the integration of a range of spatially explicit analytical techniques used in the flood risk assessment, quantification of adaptation capacity metrics, and identification of adaptation strategies. This model addresses the issue of integrating disaster risk reduction-climate change adaptation framework, which had been treated separately for the past years (Joshi *et al.* 2011).

The insurance and land-use planning sectors can generate a variety of significant insights from this study. For example, while risk-based premium pricing of insurance is an actuarial practice, the basis of such pricing should not heavily rely on the geographic location of risk but significantly consider the adaptation capacity of intended policy holders to pay the premiums and maintain insurability for a long-term. The government can play an important role in maintaining a private insurance market with risk-based premiums (LeBlanc and Linkin 2010) by providing financial subsidies to homeowners in areas at very high flood risk with very low adaptation capacity (e.g. low income, severe disability, significantly flooded properties, etc.. Through this approach, public-private partnership is enhanced and allows the comprehensive planning for disaster risk reduction and climate adaptation.

Whilst insurance policies offer an opportunity of transferring risk, these should not be used as a tool to encourage urban development on areas with highest risk. However, Brisbane City has the legacy of past poor land uses planning leaving homeowners in locations at high risk (van den Honert and McAneney 2011). At the time when the flood hit the region, the Queensland Development Code does not even regulate the construction of building in areas at risk of flooding (QFCI 2012); hence, amendment is recommended to consider not only the risk for flooding but also the climate adaptation capacity of the area/region. To improve the urban development in the City, the Queensland Flood Commission of Inquiry (QFCI) recommended strategies to "flood proof" the City. These include specification of flood immunity level, redesign of residential houses and commercial buildings with water resistant materials, setting minimum freeboard level, operations of "property buy-back" and "land swap" programs, and amendment of the Queensland Development Code to regulate the construction of buildings in areas at high risk to flooding.

4.3.2 Critical Water Supply Network Vulnerability Assessment

Considering that water supply problem during the January 2011 flood, which had been also experienced during the January 2013 flood, was more on water turbidity (Keller 2013 and News Limited 2013), this study examined the vulnerability of water supply by identifying the potential flow of turbid water along the trunk-reticulation mains. Using the results from the flood risk and adaptation capacity assessments in the water supply network vulnerability assessment, eight (8) out of 107 trunk-reticulation main connection points (as potential entry points of turbid water) were assessed as highly vulnerable critical water supply assets being found within areas of very high flood risk and very low adaptation capacity (Table 3).

Using the highly vulnerable critical electricity assets as flag junctions (see brown square dots in Figure 4) in the Utility Network Analysis of ArcGIS 10, the potential path of turbid water through the trunk-reticulation mains was traced and the total linear kilometer was then calculated. Results of the analysis revealed that turbid water may flow along 246 km water distribution lines in the North East and North West using the January 2011 flood event. These comprise 56% of the water pressure main within the study area may potentially affected by supply of turbid water.

Table 3. Counts of highly to very highly vulnerable critical water supply network assets

Water Supply Network Asset	Total	Highly to Very Highly Vulnerable	Percent of Total
Pressure Gauge (No.)	13	0	0
Flow Meter (No.)	61	11	18
Booster Pump (No.)	1	0	0
Control Valve (No.)	1990	268	13
Fitting (No.)	2011	205	10
System Valve (No.)	5010	636	13
Trunk-Reticulation Main Connections (No.)	107	8	7
Pressure Main (Length in Km.)	435	246	56

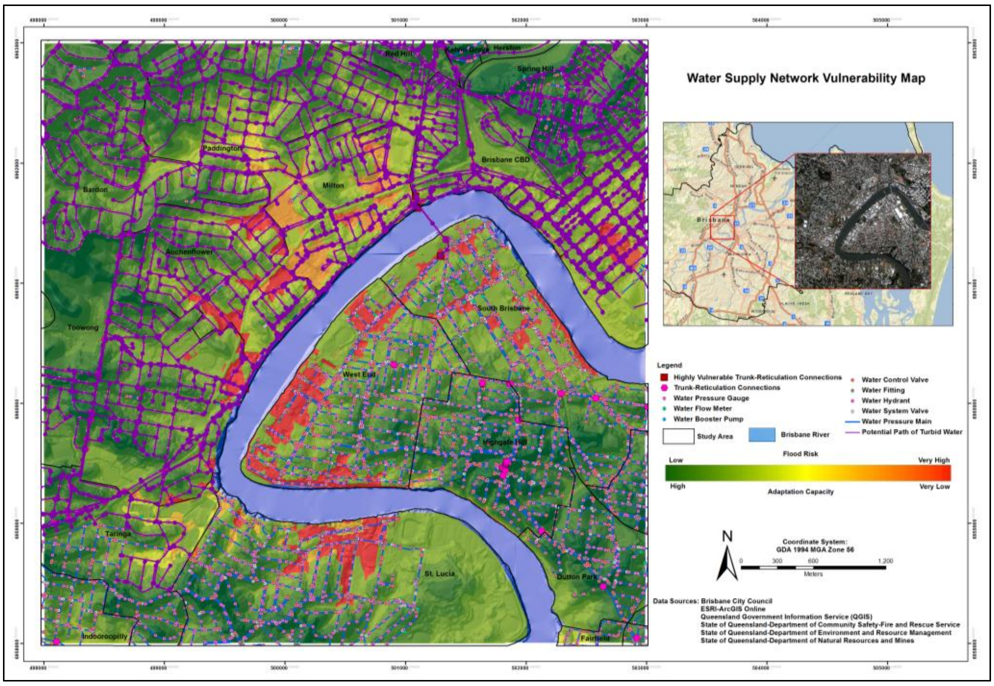


Figure 4. The generated water supply network vulnerability map of the study area

The results from these analyses can assist water supply industry to evaluate the susceptibility of water system to “dirty water” event. The analytical tool and the information generated from this study can help alleviate ranges of consequences or impacts such as water-borne diseases from any flood event. During the January 2011 flood, no report has been made regarding any breakdown of water supply infrastructure and water shortage except for the quality of drinking water in some areas. Nonetheless, it is noteworthy to take into account the potential flood impacts that may disrupt the entire water supply system. Table 3 identified the highly and very highly vulnerable water supply network assets that can be potentially harmed in the future floods. Without the mitigation measures, the possible implications for water supply infrastructure include reduced security of supply and increased risk of fluvial flooding to water supply/treatment infrastructure (DEFRA 2011). As such, climate threats to water supply should be managed according to some lessons learned such as (The Royal Academy of Engineering 2011):

- To focus on new inter-disciplinary approaches by integrating social and economic solutions with the current engineering solutions;
- To implement distributed water systems rather than centralised water systems;
- Water recycling with conscious on energy implications of recycling water;
- Use of smart meters and intelligent pipework to reduce leakage, monitor turbid water, among others.

During the 2010/2011 floods, the supply of drinking waters was maintained to meet the demands of consumers in south-east Queensland. However, this was constrained by the suspension of water treatment operations at Mt. Crosby and North Pine dam (QFCI 2011). To improve the quality of water during flood events specifically in the South East Queensland and Brisbane areas, Keller (2013) recommended an engineering modification by adding high quality water from the Advanced Water Treatment Plants (also known as water recycling plants) directly into the water treatment plant (i.e. Mt. Crosby Plant) rather than the Wivenhoe Dam. Accordingly, the advantages of this significant change include the following (Keller 2013):

- Generating up to 50% of its usual water production directly from the recycled water;
- “Dirty” river water could have been taken in and treated with the dilution from the purified recycled water;
- Pumping energy would be substantially less by not going to the dam, the high water quality could be maintained, and it would avoid losses through evaporation and infiltration from the dam.

5. Conclusions and Recommendations

In the aftermath of the devastating 2010/2011 floods in Queensland, the Australian governments and the Queensland Reconstruction Authority (QRA) sought to plan and build stronger, more resilient communities in the future.

Linking flood risk assessment with adaptation capacity assessment was the innovative technique developed in this study. Generated from complex spatially-explicit analytical methods, the flood risk-adaptation capacity index-adaptation strategies (FRACIAS) linkage model was then discussed on how it can help to address issues on insurance and land-use planning. This includes the role of the government in the maintenance of private insurance market through the provision of financial and urban development support to areas with very high flood risk and very low adaptation capacity.

This study also examined the vulnerability of critical water supply network to climate risk and the implications if services are disrupted. Although the January 2011 flood in Brisbane did not significantly damage the water supply system, there is still need to improve the quality of water supply. Extreme weather event may cause significant disruption of water supply on areas with very high flood risk and very low adaptation capacity. This study explored different adaptation strategies to reduce future risk both to the quality of water supply and the physical conditions of critical water supply network.

To improve this study, the following are some factors recommended to consider in the future research works:

1. Integration of hydrologic/hydraulic components and climate change factors in analysing flood hazards;
2. Vulnerability assessment of all critical water network assets (not only the trunk-reticulation connections) that might be subject to flood damages that could result in undesirable consequences; and
3. Vulnerability assessment of electricity supply, roads and rails, communication, sewerage, and storm water infrastructures.

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