Flood hazard simulation for development plans in urban environment: a case study in Naga City, the Philippines

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Abstract

Accurate and detailed terrain model are essential for hydrodynamics modelling especially in urban area. However, one of the main problems is frequent changes of land use in major cities, where frequent updating of the digital terrain model (DTM) for flood modelling might be needed. This paper presents one of the feasible approaches to assess the impact of developments on flood behaviours in an urban area. The input terrain model for hydrodynamic modelling is constructed through integrating different elevation datasets derived from various sources. Finally, the impact of the development on flood behaviour is made through detailed investigation on changes in flood hazard area.

In the Digital Terrain Model development, the semivariogram of the geostatistical approach is used to investigate the effect of integrating various sources of elevation datasets. Furthermore, four interpolation methods were used for terrain interpolation, namely Australian National University's Digital Elevation Model algorithm (ANUDEM), Kriging, Polynomial and Triangulated Irregular Network (TIN). The assessments of the terrain models are based on the “Percentile Vertical Accuracy Assessment”, the distribution of errors and visual assessment of the DTMs. In this study, it was found that the DTM produced by Kriging is better than the DTMs produced by other interpolators and it fits with the requirements for the flood modelling purpose. In conjunction, two sets of Digital Surface Model (DSM) were constructed to represent the situation of Naga City, before and after the developments. The flood modelling is based on the 1D and 2D SOBEK flood model that used to simulate the flood events of 2, 5, 10 and 17.5 years return period flood.

According to the results, it was proved that by simply elevating ground terrain in particular areas might not be a good solution for flood mitigation. This approach could create another flood problem in vicinity area.

Keywords: Geostatistical, DTM, DSM, ANUDEM, TIN, Polynomial, Kriging, 1D2D SOBEK

1.0 Introduction

Rapid and uncontrolled urbanization in developing countries has become one of the major issues in flood hazard and risk management. This is certainly one of the major environmental problems in the developing world, today and in the years to come. Inevitably, urbanization has considerably influence on rainfall runoff process and flood behaviour. Buildings in urban area would complicate the flow of the floodwater and it becomes a great challenge in predicting the route. In urban area, excessive water from heavy rainfall easily converted to run-off over paved surface, and due to improper development plans, the infiltration rate becomes less and increase the potential of flooding. In most cases, improper development especially in developing countries might ignore above-mentioned impact, thus increases flood hazard and risk to the surrounding community. Today's development is hydrodynamic modelling has enabled the combination of one and two-dimensional models. The one-dimensional hydrodynamic model can be used to represent open channel flow, for instance river, whereas the two-dimensional model is useful for flow over floodplain. The two dimensional model, especially in urban area requires detailed and accurate terrain model, which quality depends on the acquisition techniques and the characteristics of terrain under consideration. The main objective of this research is to generate DTM and DSM of the study area which also consider current and future development plans in the study area. The next step focuses on flood simulations and development impact assessment.

2. 0 Study area

Naga City is located in Bicol region, at the south-eastern tip of the Philippine island of Luzon. Located about 377 km to the south of Manila, Naga City is well known as a fast-growing area (see figure 1.0). Naga City has the largest population among 35 municipalities in Camarines Sur, which population covers about 8.9 percent of the total population of the province (Naga City Government Philippines Business for Social Progress, 2001). Naga City is considered the heart of the Bicol region, consisting of 27 Barangays on the land of 7,748 hectares. The main portion of The Naga City is located in relatively low and flat topography that often inundated by flood when water from the Naga and Bicol River overflow. Thus, substantial discharge from both rivers and heavy rainfall during monsoon usually ends up with severe flooding. .

Figure 1.0: Naga City

3.0 Data collection and research methodology

The whole methodology begins with data collection process and followed by the generation of DTM and DSM, flood modeling and development impact assessment. The data collection phase is divided into 4 major groups; 1) elevation or topographical data, 2) land use and land cover, 3) recent and future development plans and 4) rainfall and flood depth during super typhoon called Nanmadol (see figure 1.1). The first phase focuses on elevation data preparation, analysis and integration. In order fill gaps in the available elevation data, additional elevation points were collected. Besides, it also focuses on updating terrain data due to recent and future developments. In general, the elevation data is derived in various forms, for instance points, line and polygons, and these data were aggregated into ground terrain and man-made features. Further aggregation is made to separate the elevation data into current and future situations. The second phase of the research devotes for the construction of DTMs and DSMs. The DTMs are produced using different interpolation methods and based on certain quality assessments the best DTM is selected and further integrated with the man –made features to produce the DSMs of the study area. The 1D2D SOBEK flood model is used to simulate 5 recurrence intervals of flood events. The flood calibration is done base on flood depth information derived from the field observations (this data were collected by other researchers) after the flood event caused by super typhoon called Nanmadol that equivalents to 10-years return period of flood. Basically, the calibrations of the flood models are based on surface roughness and building structure. The calibrated surface roughness and the suitable building representation are used in the flood modelling. The surface roughness value used in this study is created from the land use or land cover information. The final phase of this study focuses on the assessments of the impacts resulting from the developments. The key point of the assessment is detailed investigation on changes of flood hazard areas for present and future situations of Naga City. In addition, the definition of the flood hazard is based on the combination of flood velocity and flood depth. The following chapters will discuss further detail on the methodology.

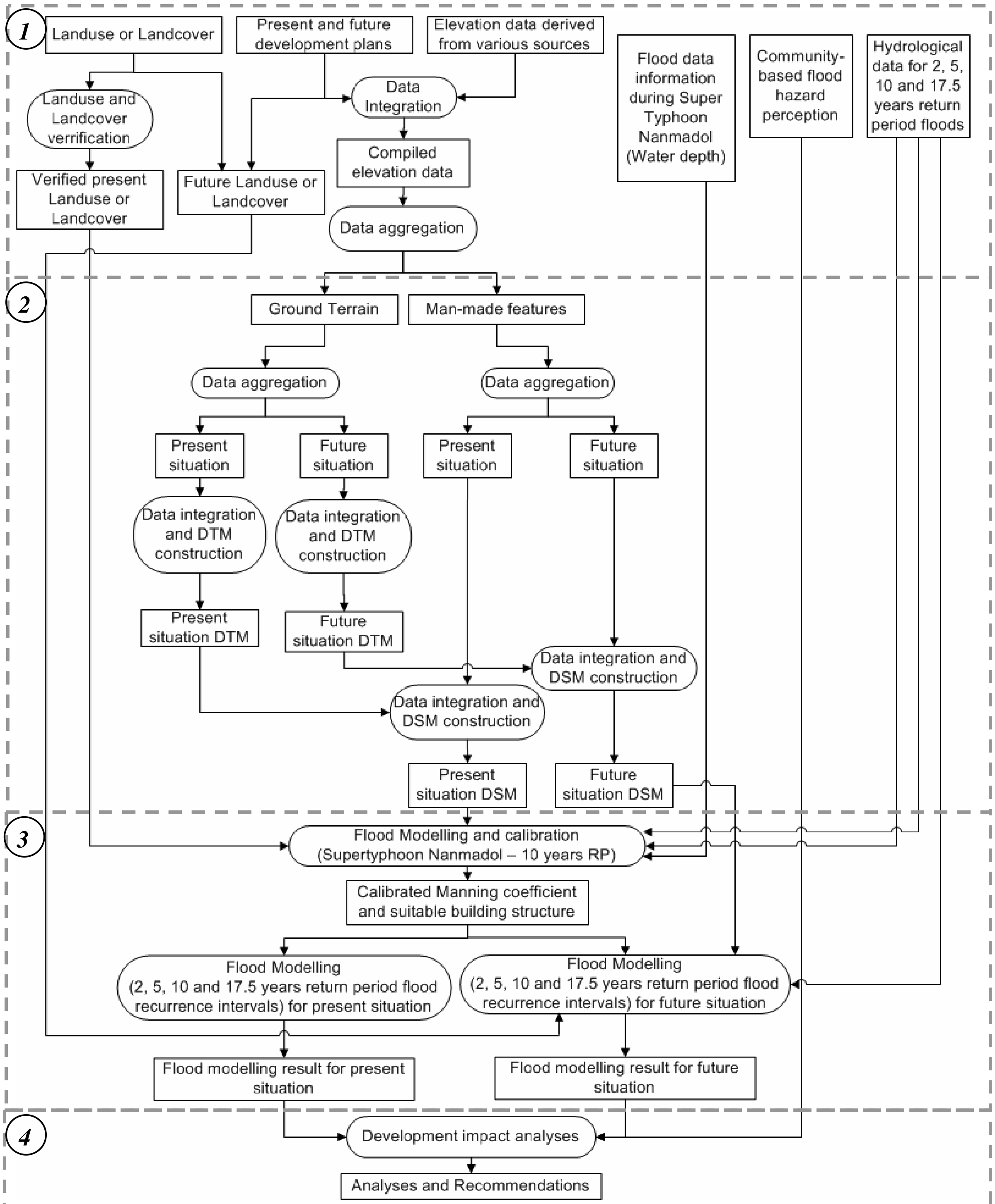


Figure 1.1: Research methodology

4.0 Results and discussion

4.1 DTM and DSM construction

This stage relies on four major; 1) elevation data preparation and analysis, 2) elevation data interpolation, 3) accuracy assessment and 4) DSM creation based on integrating natural terrain with man made terrain.

4.1.1 Elevation data preparation and analysis

The elevation dataset for DTM generation is derived through integrating various sources of elevation datasets that vary in both horizontal and vertical accuracies. In kriging interpolation, the properties of the dataset could be assessed by referring to the semivariogram. The pattern, distribution and fluctuation in elevation dataset influence the shape of the semivariogram. In this situation, Blomgren (1999) removed the clustered elevation data, which usually found over dunes, road embankments and other places with abrupt changes in topography. On the other hand, Wilson and Atkinson (2003) in their research "Prediction the uncertainty of DEM on flood inundation modelling", used ordinary kriging to interpolate elevation data in the floodplain area. The elevation dataset was the combination between the contour lines and the elevation points that were derived from GPS measurement and they found that the original experimental semivariogram of the contour lines had quite general shape. However this general shape or trend was reduced (increased variance at shorter lags than globally) when the elevation points derived from GPS measurements were added to the dataset.

Ten elevation datasets were integrated to produce DTM. These datasets vary in scale and contour interval which remarks difference in horizontal (planimetric) and vertical accuracies. The problem of integrating elevation data from different sources with different scales and accuracies lies on the fact that the elevation values in the combined dataset may lie close to each other. The challenge is to identify an appropriate approach to prioritize the datasets, to identify which of those datasets represent the true terrain elevation and to combine the entire datasets. The datasets are prioritized with 2 steps; 1) prioritization based on Nominal horizontal and vertical accuracies (based on the National Standard Data Accuracy (NSSDA)) and 2) prioritization based on data forms (spot heights and contour lines) and production date.

The contour lines are converted to points and then combined with other point form elevation datasets (spot heights). Data with higher priority score would replace the lower priority data. The replacement is done when 2 or more elevation points fall within 3 meters radius. The effect of the integration of the multi-sources elevation data is assessed by means of semivariogram analysis. The assumption is points that are close together should have less difference or high autocorrelation. Thus, high nugget value would reveal strong effect of disagreement between the elevation datasets. Certainly, the nugget effect could also attribute to the complexity of terrain features. However it was found that, the effect of data disagreement still appear when datasets with complex geomorphological features were removed. Several attempts with different integration method were used (see table 3.2) to decrease the nugget value. However, for the sake of the terrain complexity information, the nugget value was reduced from 2.9 to 2.2.

Table 3.2: The value of Semi-variogram model parameters for each dataset; the 2nd and the 3rd datasets will be used for the DTM interpolation

Dataset	Nugget	Sill	Range	Lag	Model	Number of points
50 m contour lines to point conversion interval (Dataset B)	2.9	52	4500	150 m	Gaussian	11,131
100 m contour lines to point conversion interval (Dataset A)	2.2	42	4500	150 m	Gaussian	6889
5 m block elevation average	2.2	37	4500	150 m	Gaussian	5566

At this stage, the integrated elevation datasets with low nugget value are assumed to have less disagreement between elevation dataset, less overlapping dataset, good elevation data in representing the real terrain and inevitably contain degraded complex terrain features.

4.1.2 Elevation data interpolation

In general, the DTM interpolation method should be able to preserve information of terrain features while reducing the disagreement effect of the datasets. The interpolation of the ground terrain is accomplished using 4 interpolation techniques; 1) kriging, 2) TIN,3) polynomial trend surface and 4) ANUDEM (see figure 3.2).

A Geostatistical method of interpolation or kriging is similar to probabilistic type of interpolation techniques. The weights used in the interpolation process are derived from the surrounding sample points. One of the advantages of this technique is the weights are not only based on the distance, but also on the strength of the overall correlation among the measured points (Maune, 2001). The interpolation based on the assumption that, values at a short distance are more likely to be similar than at larger distance.

Demirhan et al., (2003) in his study on the performance of several interpolation methods with presence of noise and sampling pattern had pointed out that the "Ordinary Kriging is the most robust interpolations method against noise". On the other hand, the

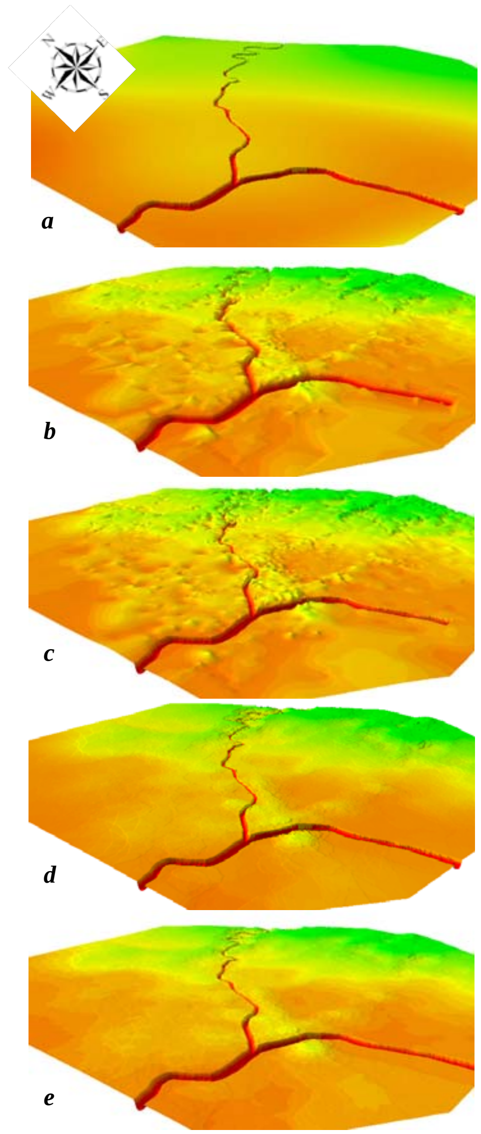


Figure 3.2: Natural terrain derived from 6th Polynomial degree (a), TIN-based terrain modelling (b), ANUDEM (c), Ordinary Kriging (100 m conversion interval) (d), and Ordinary Kriging (5 m average block) (e), visualized in 3D

deterministic interpolation approaches tries to fit a mathematical function to a set of elevation samples of known coordinate (x and y). This interpolation technique could be done either through an exact interpolation or smooth interpolation (Meijerink et al., 1994).

With coarse accuracy of data, smooth interpolation scheme might be the best way to level out the error to some degree. The fitting process makes use of various mathematical functions usually known as polynomial functions at a certain degree of complexity. On the other hand, the key point of TIN surface modelling is splitting the surface into triangular element planes (Meijerink et al., 1994) and in detailed description "TIN is a digital terrain model based on irregular array of points which forms a sheet of non-overlapping contiguous triangle facets" (Maune, 2001). Hutchinson (Geodata and Geoscience Australia, 2002) has created special software called ANUDEM (Australian National University Digital Elevation Model) for creating hydrologically correct DTM. The ANUDEM is unique in both input and output for building a good terrain model (Maune, 2001). The input data for the interpolation is not only confined to point data, but also lines which can be used to represent streams and ridges for drainage, and polygons as a lake boundary to produce a DEM that is virtually free of spurious sinks and pits

4.1.3 Assessment of the DTM quality

The quality assessment of the DTMs is divided into three main parts; 1) accuracy assessment 2) errors distribution and 3) general geomorphology of the study area. The first part makes use of the Percentile Accuracy Assessment method introduced by Maune (2001). This method is suitable for elevation datasets with non-normally distributed residuals. According to table 3.3, the ANUDEM method produced the most accurate DTM with the maximum error of 0.98 m at 80 percent of the total residuals. On the other hand, the DTM produced by the Ordinary Kriging with 5 m block average has the second lowest error with maximum error 1.00 m, followed by the Ordinary krigging on 100 m contour lines to point conversion and finally the polynomial methods.

In this study, most of the new developments and commercial areas are located in low lying area as shown in figure 3.3, where good quality of DTM is essential to represent this area. For this purpose, the next assessment will be focusing on the number of point with errors more than 1.0 within area of interest. It was found that the TIN-based surface modelling contains least number of points with error more than 1.0 m and followed by the Ordinary Kriging with 5 m block average, the Ordinary Kriging with 100 m contour lines to points' conversion interval, ANUDEM and Polynomial. The final stage in DTM quality assessment focuses on the capability of DTMs in representing the general landscape of the study area. According to figure 3.2, the DTM produced by the Ordinary Kriging with 5 meters elevation block average is able to represent the general landscape of the study area better compared to the other methods. The DTM contains back-swamp areas, natural levee and elevated areas for bridge construction. On the other hand, for the DTMs produced by ANUDEM and TIN contain large number of artificial pits and according to Raaflaub and Collins (2005) artificial pits or sink features in DTM are hydrologically serious problem and appropriate steps are needed to remove the effect. The DTMs produced by the Polynomial interpolation method contains smooth surface and in general it failed to represent the general landscape of the study area. Based on above judgements, it is concluded that the DTM produced by the Ordinary Kriging with 5 meter elevation block average will be used for the construction of the DSM.

Table 3.3: Summary on DTMs quality assessment

Interpolation method	Accuracy assessment	Number of errors with more than 1.0 m in the area of interest	Visual assessment
Ordinary Kriging (5 m elevation block average)	1.00 m (at 80 percentile)	10	Able to represent the real landscape of the study area
Ordinary Kriging (100 m contour lines to point conversion interval)	1.17 m (at 80 percentile)	19	Able to represent the real landscape of the study area
TIN	N/A	7	Contains large number of artificial pits
ANUDEM	0.98 m (at 80 percentile)	21	Contains large number of artificial pits
Polynomial interpolation methods (2nd Polynomial to 6th Polynomial)	1.66 m to 1.74 m (at 80 percentile)	> 39	Smooth interpolated surface and with very general landscape of the study area

4.1.4 Integrating natural terrain and man-made terrain

The DSM of the study area is constructed by means of combining the simulated man-made terrain and DTM. The construction of the DSMs takes into account both current and future situations of Naga City (see figure 3.3). The man-made features are created by integrating additional spatial data (e.g. roads, drainages, landuse or landcover), building footprints and development plans.

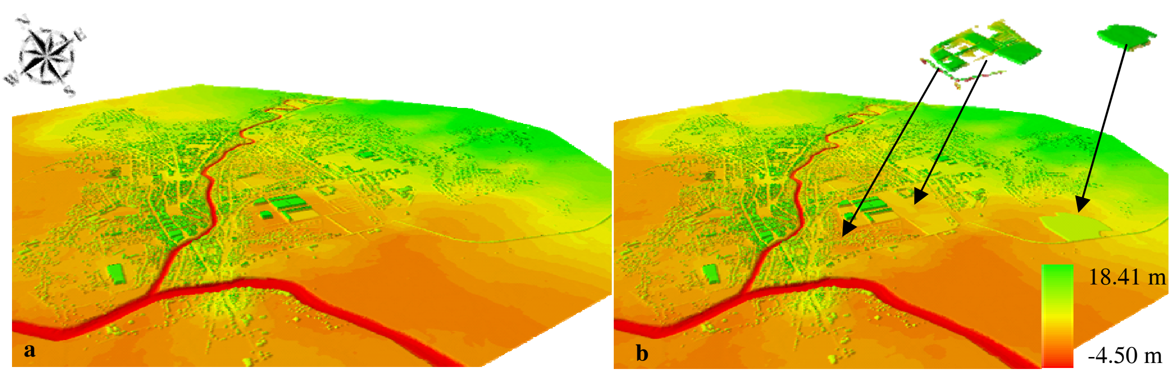


Figure 3.3: DSM represents current situation (a) and future situation of Naga City (b)

4.2 Flood modeling and flood model calibration

The Naga and the Bicol are the main rivers flowing to the Naga City and in the flood modeling process both rivers will be represented by using one-dimensional model. This model requires detailed information on the river cross sections. On the other hand, the overland flow over the floodplain will make use of the two-dimensional part and requires the DSM as the main input. In the flood modeling stage four flood events (2, 5, 10 and 17.5 years return period of floods) will take place and flood data (depth and flood extent) of the flood event triggered by the super typhoon Nanmadol is used in flood model calibration. Previous study had confirmed that the magnitude of this flood event is comparable to 10 years return period flood. The flood model calibration focuses on calibrating 2 parameters, 2 sets of building structures and 3 sets of surface roughness. In the flood model calibration process, it was found that, water velocity of rough surface building structure is higher compared to the solid block. On the other hand, building structures represented as rough surface allows water to flow farther and increase the flood extent. The obstruction from the buildings increased the flood depth and subsequently increase flood velocity at the edge of the buildings. Besides, there is no significant difference in flood depth for flood models with different set of manning coefficients. Through observation, it was found that buildings in Naga City are quite dense for both residential and commercial areas. Therefore building with solid-block structures is considered the best approach to represent the blockage effect in the flood modelling.

4.3 Development impact assessment

The assessment on impact due to developments is one based on detailed observation on changes of flood behavior and changes in flood hazard area. This assessment is crucial to predict and simulate the behavior of flood and its hazard for current and future situations of Naga City.

4.3.1 Observation on flood behavior

The flood simulation stage produces several basic characteristics of floods, for instance flood depth and velocity over time. Based on this, several other derivatives information has been produced such as inundation period and flood warning time. Figure 3.4 shows detailed work flow of this stage

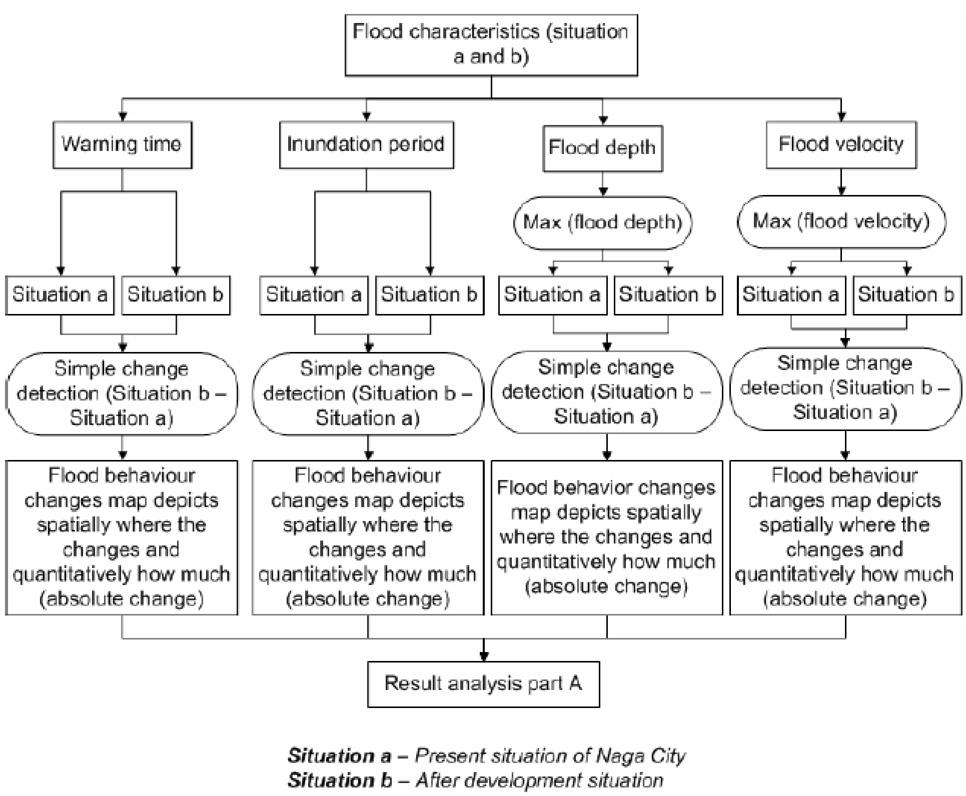
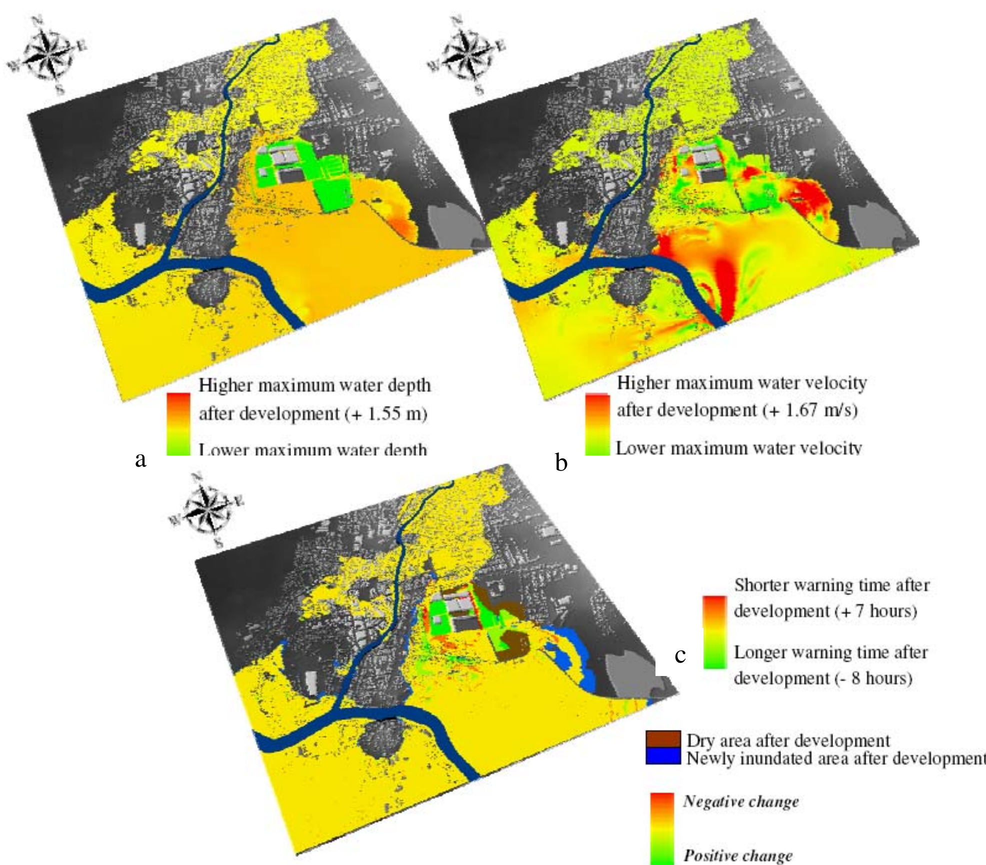


Figure 3.4: Flow chart of assessment on impact of developments based on changes in flood characteristics

Appendix 1.0 shows the distribution of Barangays in the study area. Simple change detection method has been used to show the changes of flood behaviour in the study area (see figure 3.5). The flood modelling for 17.5 years return period flood was successfully made only for 60 hours. The modelling took 6 days to complete. Nevertheless the changes in flood behaviour can still be detected as illustrated in figure 3.5. According to figure 3.5 (a), changes in maximum water depth is predicted to take place in Barangays Triangulo, Tabuco and Mabulo. Meanwhile, the highest changes of maximum flood depth are predicted in the area behind the Almeda Highway and the elevated commercial area in Barangay Triangulo. In addition, changes in maximum water velocity are also predicted in the same areas and in Barangay Sabang (figure 3.5 (b)). After 60 hours of flood simulation, some parts of the elevated commercial areas in Barangay Triangulo are still not being inundated, and for the consequence, the flood water overflows to the areas behind the Almeda Highway. In general, changes of flood behaviour for the 10 years return period flood are less compared to the 17.5 years return period flood. The impact of the development seems more localized to the vicinity areas.

In 17.5 years return period flood, changes in maximum flood depth are predicted to take place mostly in the Barangay Triangulo and some part of the Panganiban Drive area (figure 3.5 (d)). On the other hand, the maximum water depth has decreased in the elevated commercial areas in the CBD II. According to figure 3.5 (e), changes in maximum flood velocity were also predicted mostly in Barangay Triangulo. Pronounced difference in maximum flood velocity can be observed at the edge part of the elevated area in CBD II and in the residential areas in Barangay Triangulo. Areas with shorter warning time are observed in Barangays Triangulo, Sta. Cruz and Sabang (figure 3.5 (f)). Meanwhile some parts along the Panganiban Drive, Barangays Sabang and Sta. Cruz suffers long inundation period as illustrated in figure 3.5 (g). Most of the elevated commercial areas in the CBD II are predicted will not be inundated, and it seems that the flood problem in this area is transferred to another area. In general the changes of the flood behaviour in 5 years return period of flood are more localized compared to 17.5 and 10 years return period flood (figure 3.5). The changes are predicted mostly in the residential area in Barangay Triangulo. In this flood event, the impact of the small structure, for instance drainage system in Barangay Triangulo is quite pronounced, especially in the lower part of the residential area. The construction of the drainage system had eased the flood problem in this area.



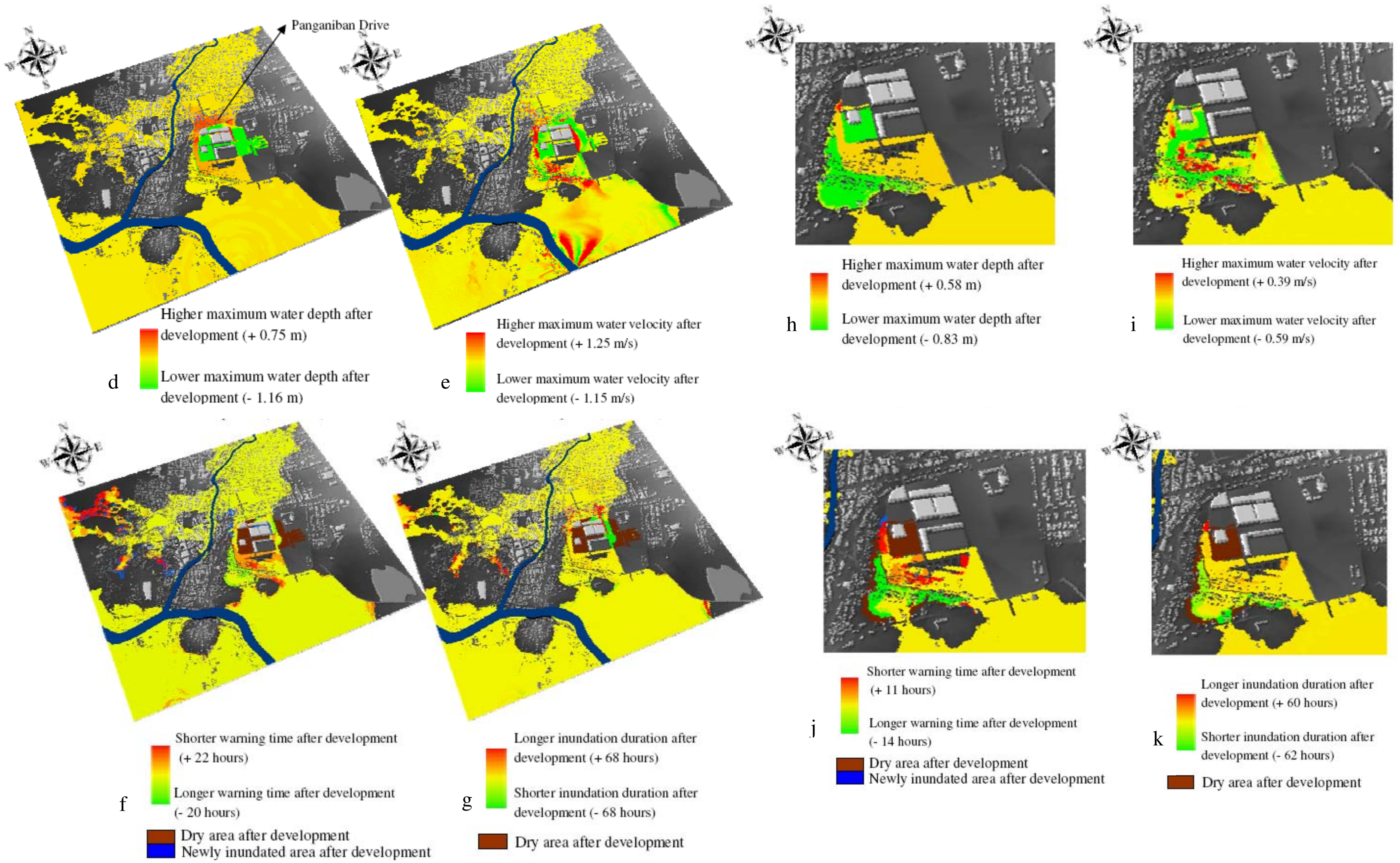


Figure 3.5: Changes in maximum water depth (a), maximum water velocity (b), warning time (c) (17.5 years return period flood), maximum water depth (d), maximum water velocity (e) warning time (f) inundation period (g) (10 years return period flood), maximum water depth (h), maximum water velocity (i) warning time and (j) inundation period (k) (5 years return period flood)

4.3.2 Flood hazard mapping

Flood hazard can be expressed in various combinations of flood characteristics, for instance, flood depth and flood velocity. Based on research by Ramsbottom et al. (2003) (see figure 3.6) flood hazard refers to the wading hazard of adults, children and also selected vehicles during flood. In this assessment, flood hazard maps for each simulation hour are created and integrated based on the worst case of hazard level at each pixel (see figure 3.7).

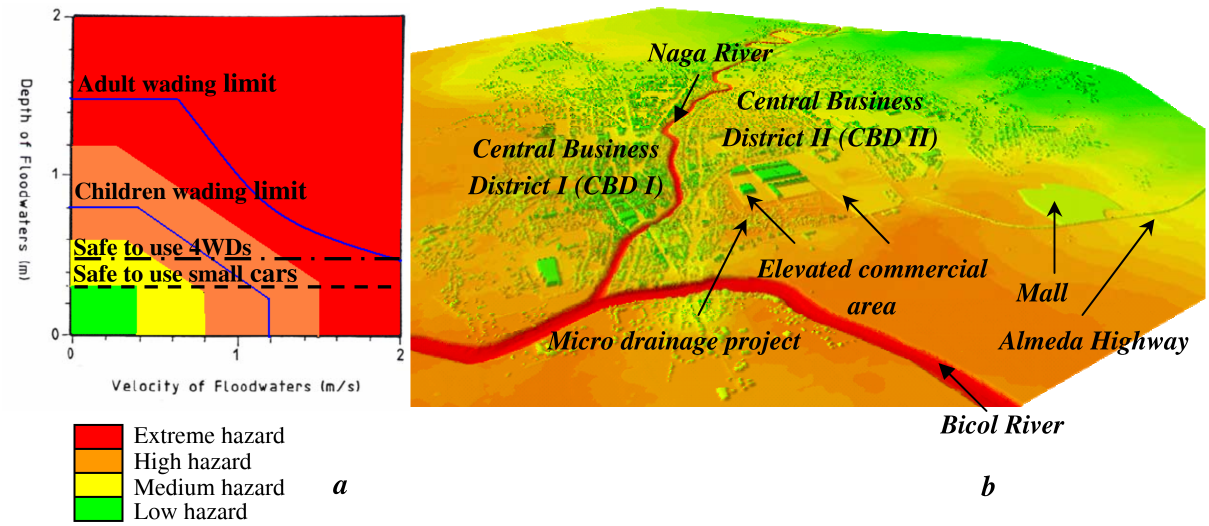
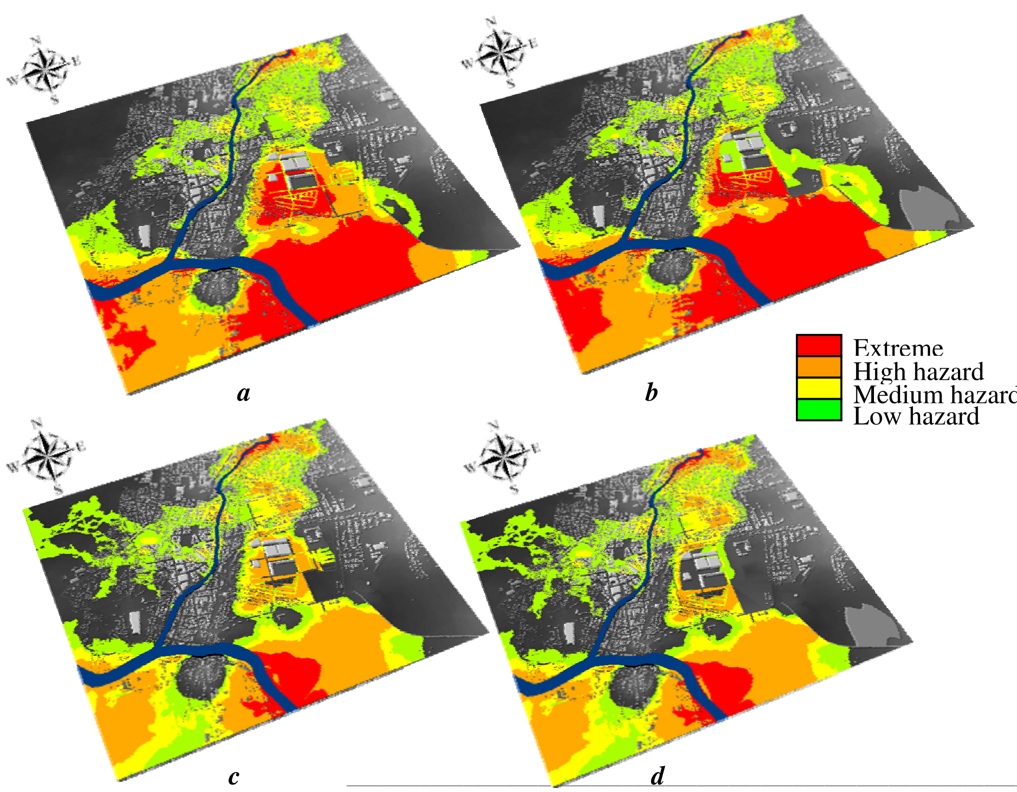
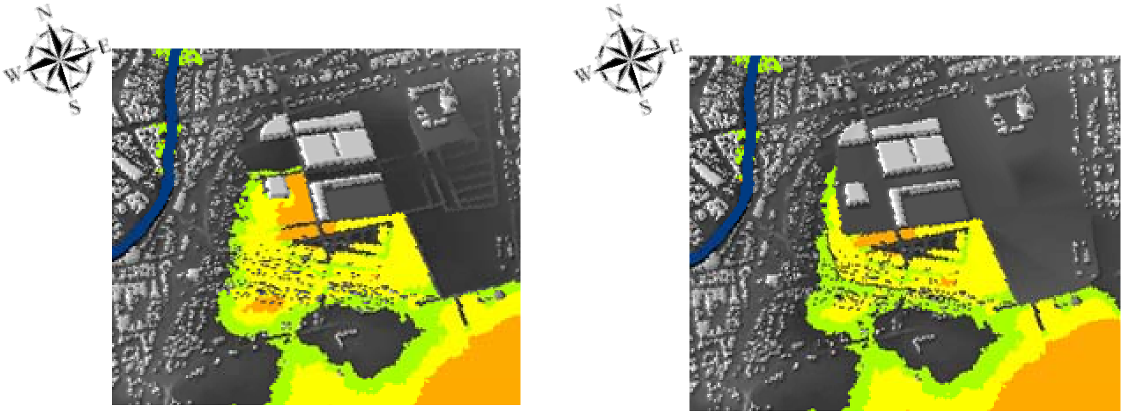


Figure 3.6: Graph that combines flood velocity and flood depth to define level of flood hazard (Ramsbottom et al., 2003) (a) and Major developments in Naga City (b)





e *f*

Figure 3.7: Flood hazard distribution for current (left) and future (right) situations of 17.5 years, 10 years and 5 years return period flood in Naga City

5.0 Conclusion

It was shown that the step by step integration of multi-source elevation datasets could be one of the cheapest approaches in constructing terrain model without precise and expensive elevation data acquisition techniques for instance, LiDAR and aerial photo. However, the integration of the elevation datasets should be made very carefully. In this case, the terrain updating process can be made through the conventional levelling and the compilation of recent and future development plans. Figure 3.9 shows detailed changes in flood hazard area in Naga City for 17.5 and 10 years return period flood. According to figure 43.9 (b), for 10 years return period flood, it is about 92 percent of the areas with the positive impact are located in commercial area. Meanwhile, areas with negative impact are mostly in the residential and other commercial areas (figure 3.9 (a)). On the other hand, for 17.5 years return period flood (figure 3.9 (d)), commercial areas account about 96 percent of the total areas with positive impact. Besides, it is about 34 percent of the agriculture areas, 21 percent of the residential areas and 13.88 percent of the commercial areas are classified in negative impact areas. It has been shown that future planning for urban area would be valuable information for flood hazard mitigation. Detailed development plans and topographic information would be essential for detailed and accurate flood modelling. Furthermore, the one-dimensional model could also be used to account the contribution of drainage network in urban area for flood mitigation and this would be very interesting information for drainage department. It also of a great important to assess the flood behaviour for any flood mitigation plans before any physical development takes place, especially in decision making process. Thus, any physical mitigation plan can be simulated and further integrated in the flow simulation, and give essential view of potential behaviour of flood. Figure 3.8 shows that this study basically can be used in flood hazard mapping, flood risk assessment and mitigation phases.

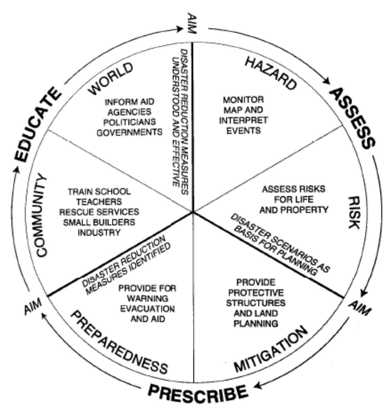


Figure 3.8: Risk management cycle; the results of this study can be used in HAZARD mapping and MITIGATION process. Source: Smith (2001)

It should be noted that the assessment of the impacts doesn't intend to oppose any development in Naga City. The simulation results rather give better ideas, overview and understanding on how floods would behave after some developments take place and subsequently it becomes essential information for flood management and mitigation processes. Development is necessary to provide current necessities and needs of the future generations. However, sustainable development may not be achieved without any effort in reducing the intensity of hazard as a result of developments.

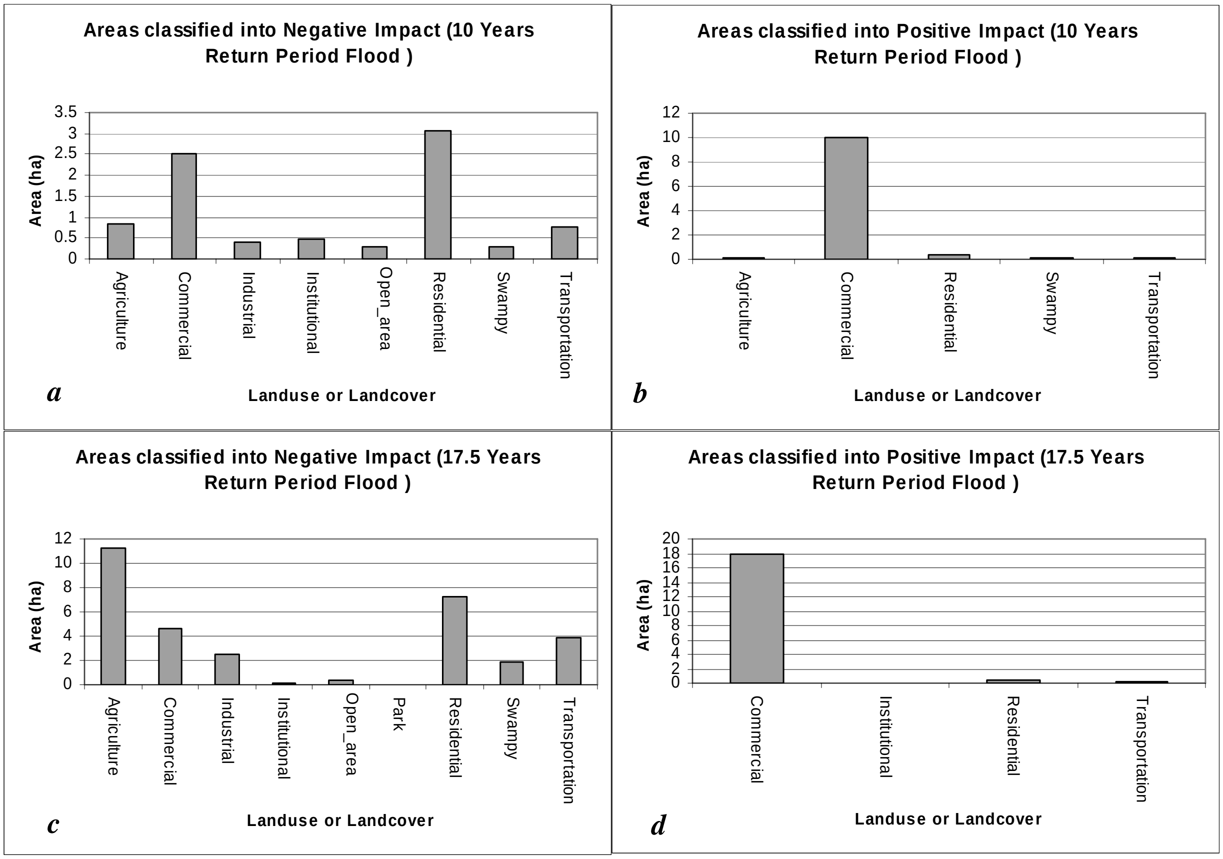
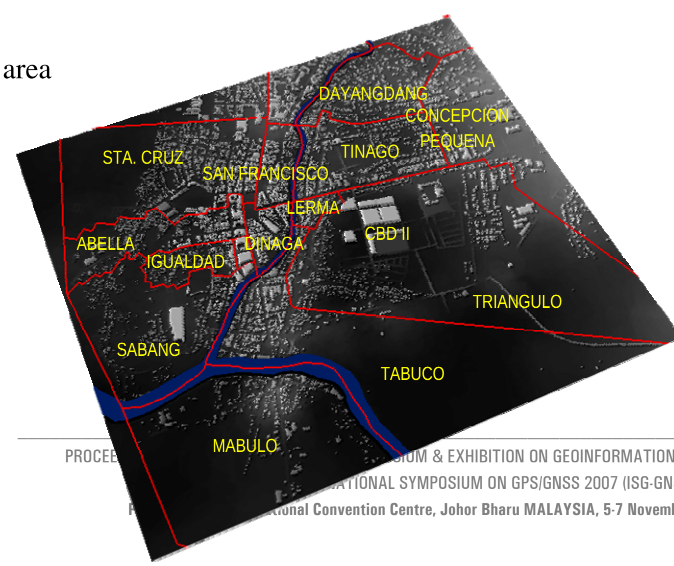


Figure 3.9: Areas classified into negative and positive impact (based on the flood hazard map) for 10 years return period flood (a and b) and 17.5 years return period flood (c and d)

Appendices

1.0 Barangays or zones in the study area



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