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Flood inundation mapping using hydraulic modelling and GIS: A Case Study in the West Creek Sub-Catchment

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Abstract: In recent years, climate change has caused extreme climate conditions. This intensifies and increases the amount of rainfall that caused floods in many regions of the world. The recent floods in Queensland, Australia provide evidence of the effects of increased climate change to the state and its population. The flash flood that occurred on the 10th of January 2011 in the West Creek catchment in the City of Toowoomba was a sudden and unexpected event making it difficult to implement flood mitigating/preventive measures. To reduce the impact of flood damage, this study aimed to develop an improved flood inundation model in the part of West Creek catchment using Geographic information systems (GIS) and the HEC-RAS hydraulic model. A digital elevation model (DEM) derived from LiDAR data was the primary data source for flood modelling. The geometric data (e.g. stream centreline, banks, flow path centreline and cross-sections, etc.) were extracted from the DEM and used in the analysis. A high resolution satellite image was used to classify land cover. Roughness coefficients were assigned according to different land cover types. Field measurements were also conducted to

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support the modelling process. These include measuring culverts, stream cross-sections, etc. The result was flood inundation map that clearly shows the spatial extent of the flooded area along part of West Creek and lower elevation areas within the catchment.

I. Introduction

THE Australian continent received unexpected rainfall during late November 2010 to mid-January 2011. This caused extensive flooding in north-west, Western Australia and in Queensland (BOM, 2011). The floods were unprecedented in extent of both the flooded area and the number of record water height levels that were reached. The Queensland floods in December 2010 and January 2011 affected 75% of South-East Queensland (Brisbane, Toowoomba and the Lockyer Valley) (Chanson, 2011; McEwan, 2012). Extreme flash floods occurred on the Toowoomba Range and in the upper Lockyer Valley on Monday afternoon 10 January 2011causing substantial losses of life and damage to property (Mason, Phillips, Okada, & O'Brien, 2012).

Figure 1. Flash flood in Toowoomba City

Because of continued urban growth and lack of regulation, land cover in urban and rural areas of the Gowrie Creek catchment has changed over time from pervious areas (e.g. soil, scrubland, forest) to large areas of impervious surfaces (e.g. concrete, asphalt, footpaths, car parks and buildings, etc.) (ICA, 2011). This has contributed to a change in the hydraulic behaviour of the catchment by decreasing the infiltration of water and increasing the volume and immediacy of surface runoff (Ediriweera, 2007).

Channel structures such as bridges and culverts built across floodplains and waterways cause obstruction to the flow of water. In addition, the relatively steep and narrow shape of the catchment, along with the intensity and speed of the runoff, contributed to the flash flooding. Small, short and steep catchments have shorter critical storm durations (length of time to flooding) than larger, longer, flatter catchments (ICA, 2011).

Mitigating the effect of floods requires both accurate and current information about the catchment characteristics and likely precipitation events (Abera, 2011). Hydraulic models have the ability to analyse the characteristics of catchments and to develop information about potential flood events. There have been many previous studies on floods in Toowoomba including flooding in West Creek (ICA, 2011; SKM, 2011). The focus of these studies has largely been on simulation and modelling of flood events to develop knowledge about how the flood events progress (Fosu, Forkuo, & Asare, 2012; Johonson, 2001). To produce reliable results these models need good estimates of catchment and precipitation data to achieve useful results. The use of high resolution imagery, together with reliable estimated LiDAR data of the catchment, along with a field survey enabled the reconstruction of flood extents and gave results that closely approximated measured water height levels (McDougall & Temple-Watts, 2012; Turner, Colby, Csontos, & Batten, 2013).

Previous studies have shown that the Hydraulic Engineering Centre’s River Analysis System (HEC-RAS) hydraulic model, combined with GIS, is effective tools for mapping inundation (Cepero-Perez, Liu, Reed, & Aschwanden, 2009). The output from HEC-RAS can be used in a GIS to map flood extents. This research focuses on applying HEC-RAS and GIS to analyse the 2011flood events in the West Creek Catchment.

The LiDAR data, high resolution remote sensing imagery and field data were used to improve the hydraulic model to simulate flash flooding of West Creek and to produce flood inundation mapping.

II. Methodology

A. Study Area

Toowoomba is located on the western side of the Great Dividing Range approximately 700 m above sea level. The Toowoomba Regional Council covers 12973.3 km^2 (Queensland Floods Commission of Inquiry (QFCI), 2011). A large proportion of the city drains to the west but also includes the far eastern areas which drain to the east of the escarpment. The terrain within the city is undulating consisting of a number of ridges and valleys which divide it into six distinct catchments. Just four catchments (East creek, West Creek, Black Gully and Gowrie Creek) were affected by the flood event of 10 January 2011. These catchments join to form the Gowrie Creek system within Toowoomba and cover an area of about 56 km^2 within council's jurisdiction. The Gowrie Creek system is at the headwaters of the Condamine River which subsequently flows into the Murray-Darling River system. The Gowrie Creek system does not contain major water storage areas, although many detention basins have been constructed in the catchment since the adoption by Council of the Gowrie Creek Catchment Management Strategy in 1999. This has been part of a broader flood mitigation strategy (Collins, 2011).

The study area was the catchment of West Creek of about 16.4 km^2 (Figure 2). It extends from the southern extent of the city north to the CBD and westwards from Middle Ridge to a ridgeline historically known as West Ridge. This catchment has moderately steep slopes with runoff travelling quickly over an impervious surface to the watercourse. The flow velocity within the stream is high because the waterway of this catchment is steep and the channel is narrow. Most of the West Creek Catchment is completely developed with residential areas in the south, industrial zones in the central areas, and commercial uses in the northern areas in and around the CBD. Almost 37% of the catchment is impervious. The waterway of West Creek is predominantly owned by Council and consists of ponds, wetlands and detention basins in the southern sections and concrete lined channels in the northern sections adjacent to the industrial and commercial areas. West Creek is crossed at ten locations along its length with the majority of structures having adequate hydraulic capability for 1: 25 year rainfall events (Collins, 2011).

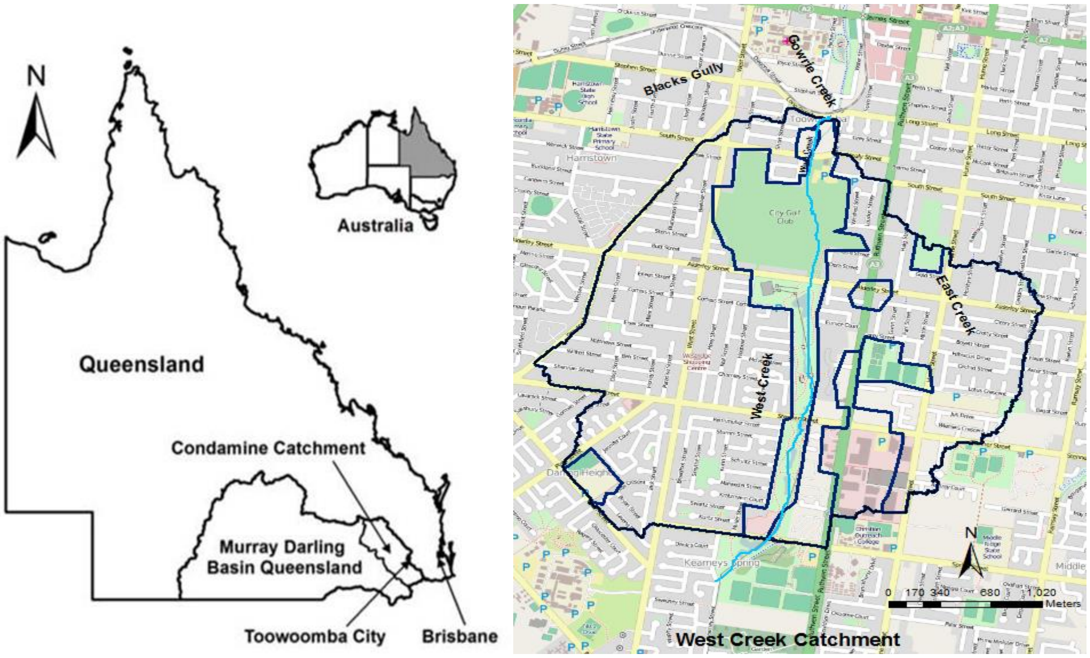


Figure 2. Study Area (part of West Creek Catchment in Toowoomba City)

B. Data Sources

The remote sensing data and field data required for the study were collected from respective agencies. The resolution of the data along with acceptable estimates give results as close to reality as possible. The data sets used in this research are:

1) Airborne Light Detection and Ranging (LiDAR) data

LiDAR data was collected by using the Optech ALTM Gemini LiDAR system flying at an altitude of 1200 m above sea level over 29 June to 16 July 2010. A configured laser scanner recorded up to four returns of each laser pulse. The average separation point was 1.0m. The LiDAR data used in this project has been documented to have 0.15 m of vertical accuracy and 0.22 m of horizontal accuracy (Schmap, 2010). These data points were classified into ground and non-ground points by the seller and delivered as a binary LAS file (Schmap, 2010).

2) High resolution satellite imagery (Worldview-2 multispectral data)

WorldView-2 imagery, captured on 10th of June 2010, was classified to create a land cover map. WorldView-2 image is the first high resolution 8-band multispectral commercial satellite image. This image provides 0.46m resolution for panchromatic imagery and 1.85m resolution for multispectral imagery. WorldView-2 focused on a special range of the electromagnetic spectrum, which is sensitive to specified features on the land.

3) Field survey data

Field data was collected from the catchment. This included cross-section elevation data at each station and a check on the types of structures in the catchment, such as bridges, culverts, dams, canals, reservoirs, etc., for use and analysis in the HEC-RAS model. The general surface characteristics of the catchment were also recorded to determine the roughness coefficient (Manning's n).

C. Methods

HEC-RAS and HEC-GeoRAS (Geospatial River Analysis System), an extension of HEC-RAS were used to simulate flash floods in the West Creek Catchment. HEC-RAS was developed by the Hydraulic Engineering Centre, a part of the Institute for Water Resources, U.S. Army Corps of Engineers (USACE, 2012b). The Research Institute developed several programs for river modelling in 1965. The first version of HEC-RAS was released in 1995 to assist in analyses of rivers, streams and channels (USACE, 2012b). HEC-RAS is an integrated system of software that is able to simulate the water flow in rivers and channels using a numerical model. This software is one dimensional which means that there is no direct modelling of the hydraulic effects of the transverse profiles. (USACE, 2012a).

HEC-GeoRAS was used to assisted with the pre-and post-processing of geometric data created in HEC-RAS (HEC-GeoRAS, 2010). It was developed by cooperation between the Hydraulic Research Engineering Centre (HEC) and the Environmental Systems Research Institute (ESRI). The most important component of HEC-RAS is the steady flow water surface profile. It is used to compute the water surface profiles of flash flood events to simulate and create flood inundation maps. The water surface profile calculation is based on the one dimensional energy equation (Knighton, 2014):

$$\boldsymbol{Z_2} \ + \boldsymbol{Y_2} + \frac{\boldsymbol{a_2\ v_2^2}}{\boldsymbol{2G}} = \ \boldsymbol{Z_1} + \boldsymbol{Y_1} + \frac{\boldsymbol{a_1 v_2^1}}{\boldsymbol{2g}} \qquad (1)$$

where:

$\boldsymbol{Z_1},\ \boldsymbol{Z_2}$ = Elevation of the main channel inverts

$\boldsymbol{Y_1}$, $\boldsymbol{Y_2}$ = Depth of water at cross sections

$\boldsymbol{V_1}, \boldsymbol{V_2}$ = Average velocities (total discharge/ total flow area)

$\boldsymbol{a_1}, \boldsymbol{a_2}$ = Velocity weighting coefficients

$\boldsymbol{g}$ = Gravitational acceleration

$\boldsymbol{h_e}$ = Energy head loss

The energy loses are evaluated by using the Manning equation, an empirical equation for gravitational flow and expansion/compression coefficient modified by the velocity (USACE, 2010).

Use of the geometric representations DEMs (digital elevation models) and TIN's (triangular irregular networks) make modelling of streams easier and less expensive. The combination of an ArcGIS extension with the hydraulic model HEC-RAS represents the platform for flash flood simulation and effective for water flow in channels. Furthermore, HEC-GeoRAS is an extension of the basic program HEC-RAS and has a suite of procedures, instruments and utilities for processing geospatial information in ArcGIS (USACE, 2012a). Figure 3 shows the steps in the hydraulic model.

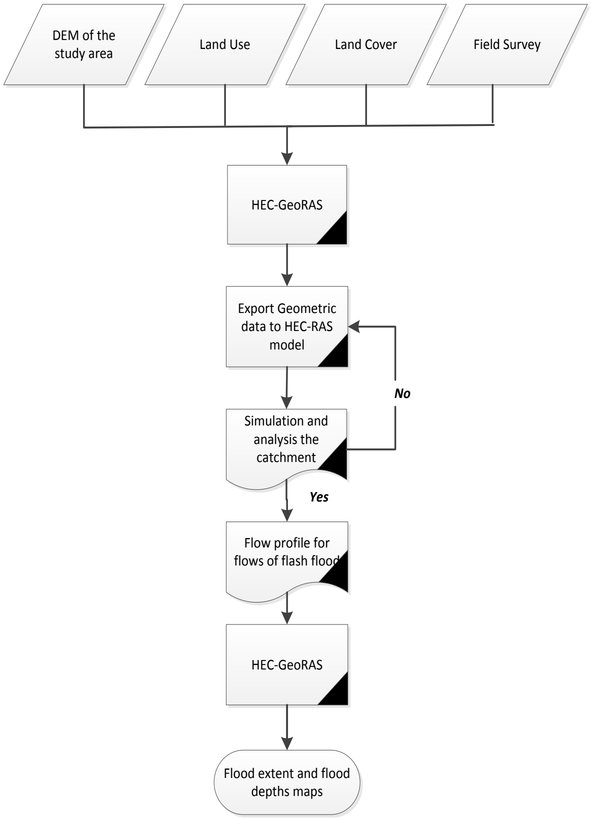


Figure 3 Steps for HEC-RAS modelling

1) Data pre-processing

a. Creating Surfaces from the LiDAR Data

A DEM with one metre resolution was created from the LiDAR ground data in the study area by using an IDW (inverse distance weighted) interpolation method in ArcGIS.

b. Sub-Catchment Delineation

The Arc Hydro extension of ArcGIS was used to extract the catchment and sub-catchment boundaries and to identify the drainage networks from the DEM.

c. Catchment Surface Classification

WorldView-2 imagery was classified into land cover types using ERDAS imagine (2013 version 2) software. Five land use categories (residential, concrete, water, trees, and open areas) were identified to produce the land cover map (Figure 4). These were used in the hydraulic model to determine the Manning's n values.

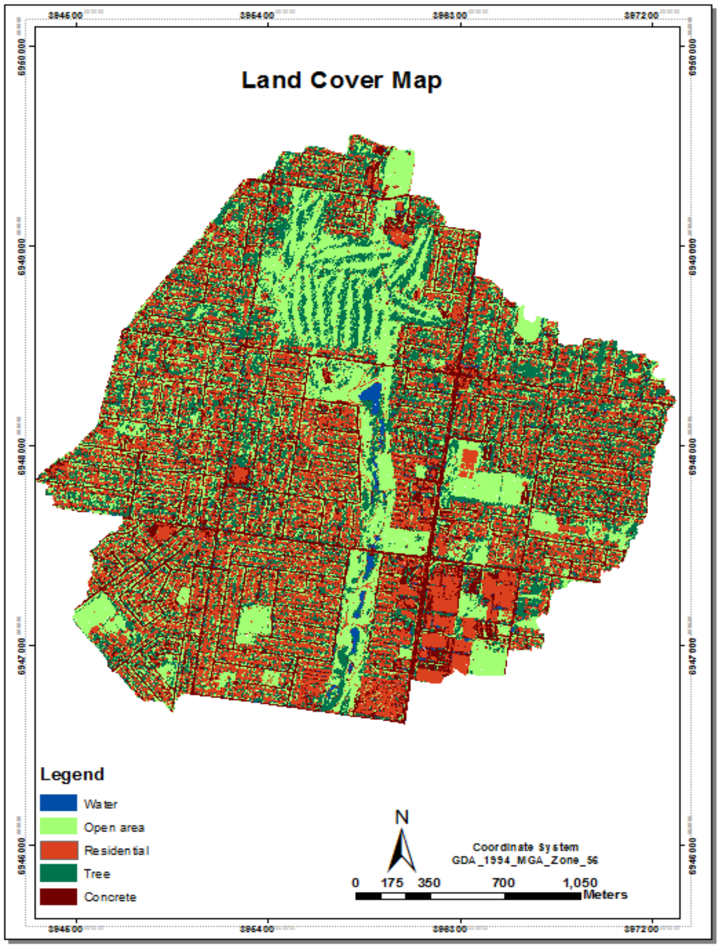


Figure 4. Land cover map of West Creek Catchment.

2) Hydraulic Analysis

The main input data for the model is the DEM. From this data, geometric data can be generated for the model by using HEC-GeoRAS. HEC-GeoRAS is specially designed to process geospatial data for use with the HEC-RAS model. It is used for pre-and post- processing of the data to generate an input file for HEC-RAS. Several procedures, tools and utilities of HEC-GeoRAS are used to create the geometric data which included stream centre lines, main channel banks, flow path centreline, cross-sectional cut lines and culverts. Another important hydraulic dataset is the land use/ land cover map which is used to identify the Manning's coefficient in terms of the type of material and size. The attribute data are added to the geometric data. The complete data for the hydraulic modelling is known as River Analysis System (RAS) layers. These data are then exported to HEC-RAS.

HEC-RAS is a one dimensional flow model in which the stream morphology is represented by a chain of cross sections indexed by channel stations. The cross-section is defined by a series of lateral and elevation coordinates that are normally acquired from the DEM. Figure 5 shows the geometrical data model setup.

This model has the ability to analyse, modify and filter the geometric data. The field survey is used to obtain information such as dimensions of culverts, channels structures and types of materials for Manning's n values. This information is used to define the hydraulic model.

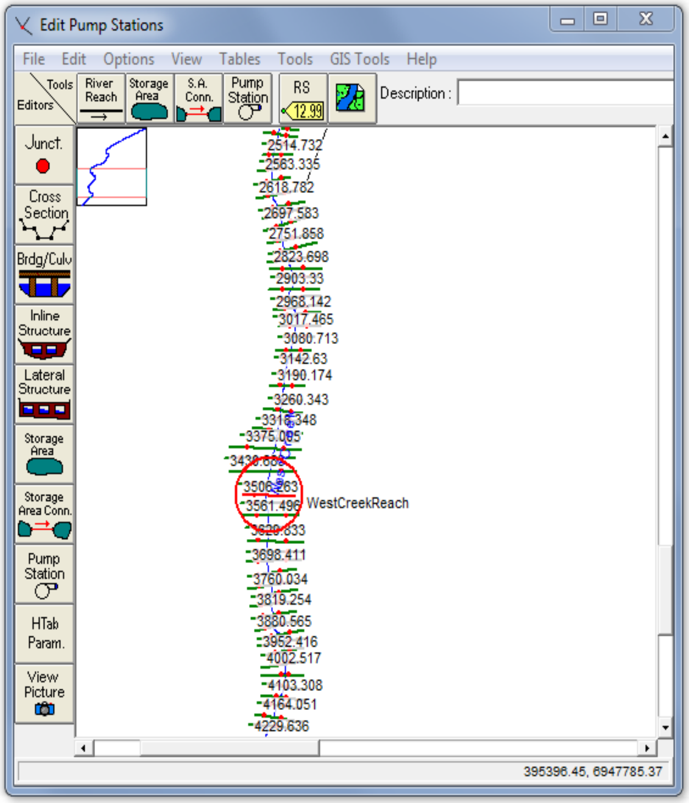
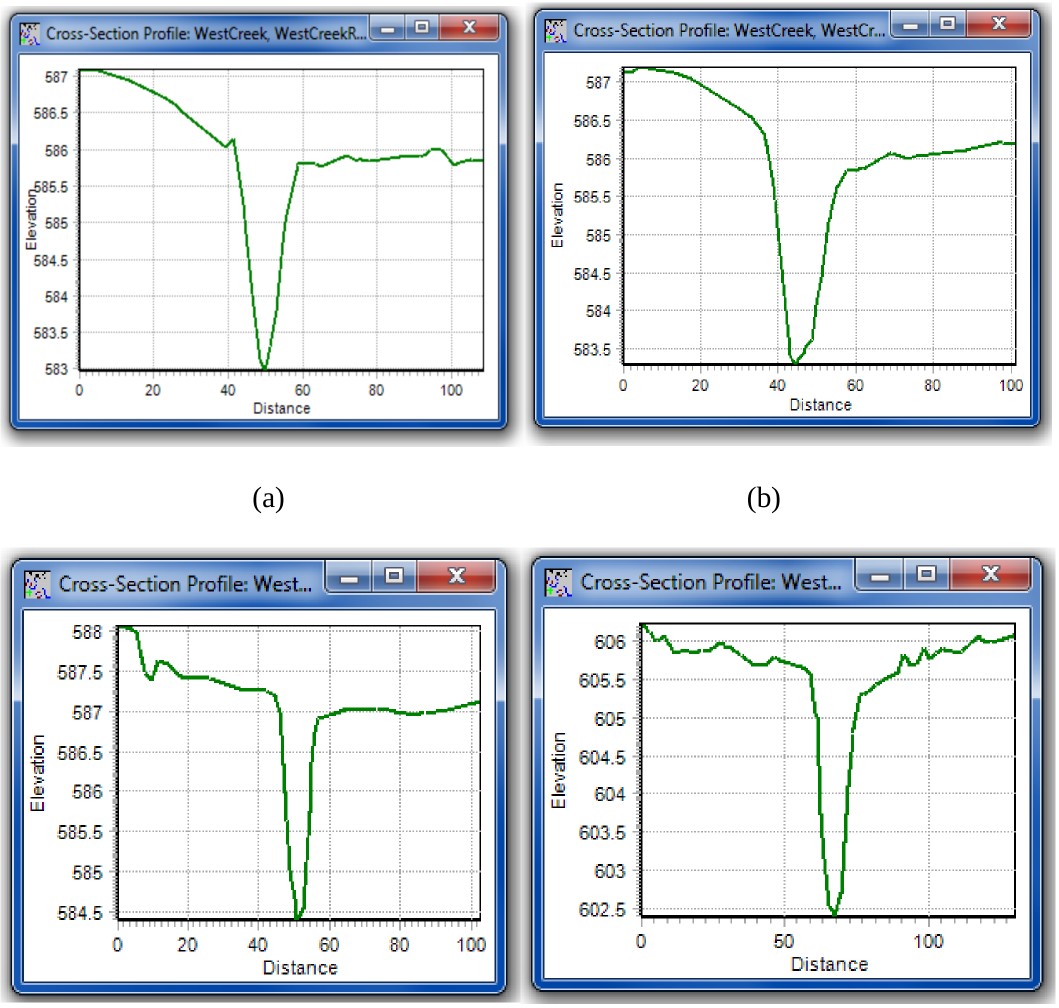


Figure 5 Geometrical data model setup

The geometric data such as cross sections have the ability to cover the entire floodplain. It is essential that the geometries of a HEC-RAS model be designed to create flood mapping analysis to cover the areas vulnerable during flood events. Figure 6 shows cross section profiles of the stations circled in Figure 5.



(a) (b)

(c) (d)

Figure 6 (a-d). Cross sections views for stations in West Creek Channel

Figure 6, shows that HEC-RAS can create geometric data for the stream profile. Cross-sectional data is essential for analysis of the channel at 100m intervals. The reliability of the geometric data in turn depends on the reliable estimates of DEM. In this research, 2500 cross-sections were generated. The cross-section profile shows the elevations, width of the channel, right channel bank (RCB) and left channel bank (LCB).

3) Flow Data and Boundary Conditions

Steady flow data were used to simulate the flash flood in the catchment area. Both stream profiles and flow rates are the main input data for the steady flow calculation. The peak discharge volume was taken from the technical report on the Toowoomba flood on 10 January 2011 (Collins, 2011). Under steady flow boundary conditions the downstream slope for normal depth computation is 0.0018. The flow regime in steady flow analysis was subcritical to simulate the flood in Toowoomba city on Monday 10th January 2011. The HEC-RAS results were exported into ArcGIS to generate the flood inundation map. This process creates the Server Compact Edition Database File (SDF) in the working directory folder which is needed for export to ArcGIS.

4) Flood extent/depth generation

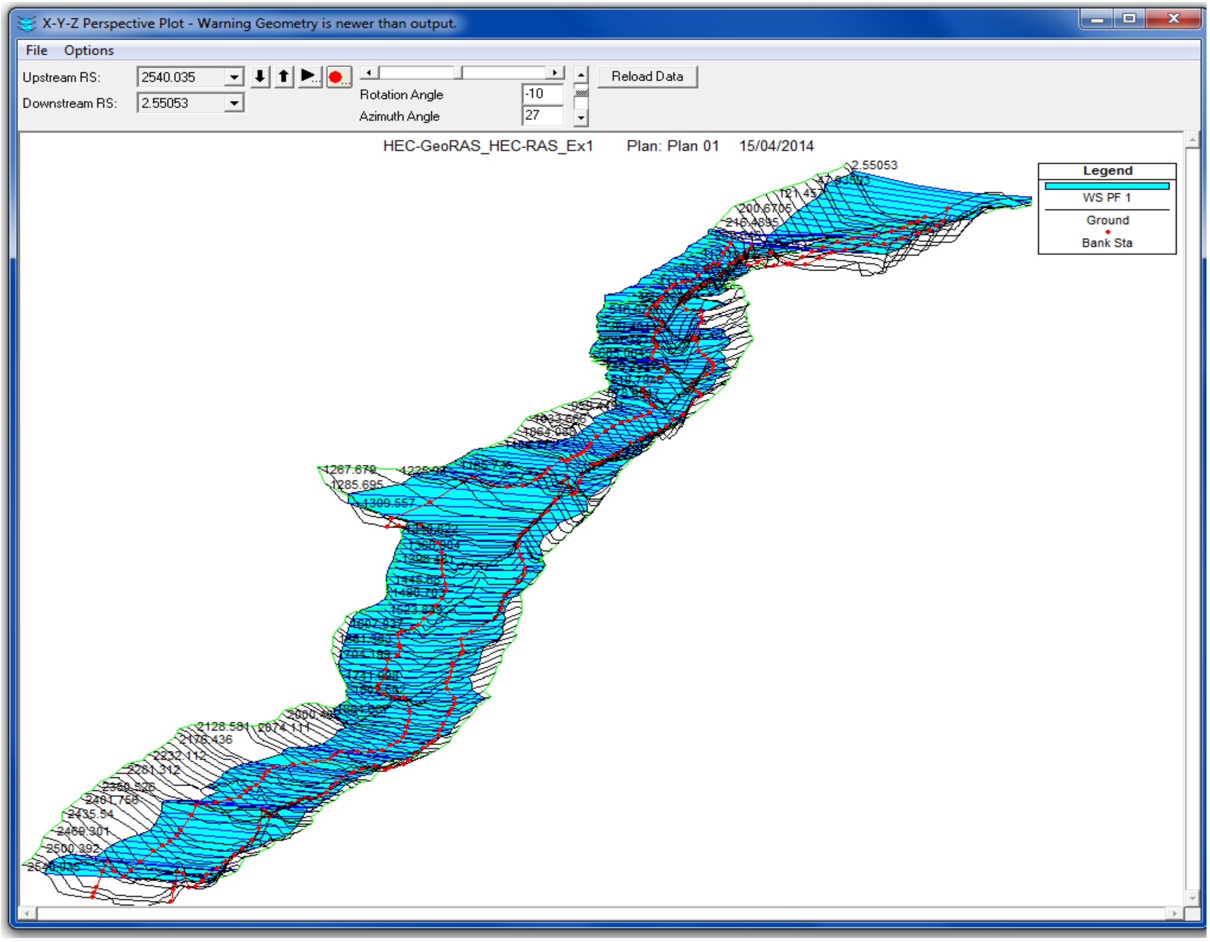
In HEC-GeoRAS, the SDF file was converted to an Extensible Markup Language (XML) file. The River Analysis System (RAS) data was imported into RAS mapping in GeoRAS to create a boundary polygon which shows the extent of the flooding. This was done by using the Water Surface Profile (WSP) in RAS mapping. The results were used to generate the extent and depth maps that show the flood events on 10th of January 2011.

III. Results and Discussion

Processing and editing the modelling of the West Creek Catchment resulted in the creation of a flood extent and water depth map over different periods of time. Analysis of these maps was done to explain various scenarios.

The extent of the flood water depends on the resolution and reliability of the digital elevation model. It helps in analysing the performance of the channel to simulate the flood with a high similarity to the actual flood. This feeds into emergency planning such as evacuation planning for areas that are more floods prone.

The flow rate data was added to the HEC-RAS model. A steady flow condition was chosen to compute and simulate the flood event. The profile of the stream and analysis of the peak flow was done to simulate the flash flood that occurred in West Creek Catchment. The steady flow analysis used high resolution elevation and flow rate data. Figure 7 shows how the flash flood occurred in the West Creek Catchment at each 100m station.



X-Y-Z Perspective Plot - Warning Geometry is newer than output.

Upstream RS: 2540.035

Downstream RS: 2.55053

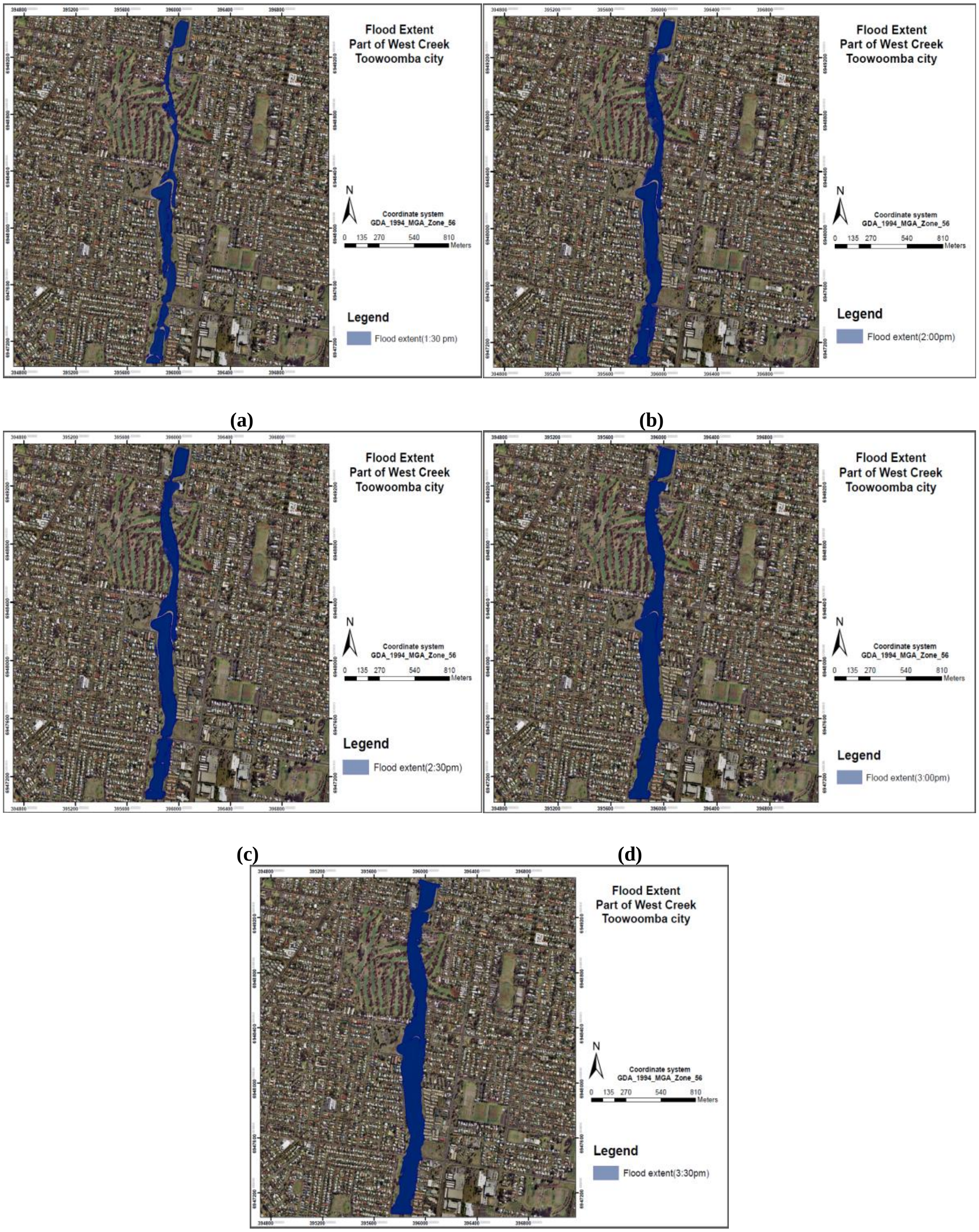
Rotation Angle: -10

Azimuth Angle: 27

HEC-GeoRAS_HEC-RAS_Ex1 Plan: Plan 01 15/04/2014

Figure 7. Flood Simulation in West Creek.

This creates flood inundation mapping at different periods of time. The inundation maps were produced to illustrate the flood extents which show the flood event of 10th of January in 2011 in West Creek in Toowoomba city from 1:30pm to 3:30pm. The results in figure7 are reasonable when if compared with the pre-existing flood hazard maps and field observations. Figures 8 (a-e) show the flood inundation mapping in the study area from 1:30pm to 3:30pm.



(a) (b)

(c) (d)

(e)

Figures 8 (a-e). Flood extent mapping in the study area from period 1:30pm to 3:30pm.

The inundation maps illustrate the flood extent at different time periods. The spatial distribution of the flooded area is located in areas with relatively low relief. Eleven point one hectares was inundated at 1:30pm (Figure 8a). The inundated area increased to 21.2ha, 25.1ha and 28.8 ha at 2:00pm, 2:30pm and 3:00pm respectively (Figure 8 b, c, and d). This shows the flooded area expanded rapidly. A peak flow at 3:30pm the flooded area was 31.8ha (Figure 8e). These areas are close to the channel and include low lying residential areas. The maps developed from the modelling reliability identify the affected areas.

The flood expanded steadily over the period from 1:30pm to 3:30pm because there was no "free flow" of water out of the channel. This caused the area to flood to a higher level. The minimum flood extent occurred in the area near the Culverts, which were blocking water movement and reducing the water runoff. Some of the areas have high banks which restrict the channel area and impede the flow. The maximum flood extent was shown to occur in impervious areas which have a low infiltration percentage of water to the underground so causing increasing runoff on the surface. Table 1 illustrates the flood extent for every 100m across at different times.

Station (m)	Flood Time, hour					Station (m)	Flood Time, hour				
	1:30pm	2:00pm	2:30pm	3:00pm	3:30pm		1:30pm	2:00pm	2:30pm	3:00pm	3:30pm
	Extent (m)	Extent (m)	Extent (m)	Extent (m)	Extent (m)		Extent (m)	Extent (m)	Extent (m)	Extent (m)	Extent (m)
100	80.000	92.000	105.000	125.740	157.440	1400	22.280	124.000	129.400	143.150	158.440
200	81.000	89.000	101.000	104.870	117.860	1500	22.550	67.500	70.280	95.590	106.900
300	70.000	91.630	112.000	123.120	124.000	1600	18.340	43.500	59.990	69.500	98.580
400	32.000	80.490	107.600	108.800	129.700	1700	20.840	32.000	52.790	85.320	89.320
500	34.000	85.000	112.810	136.360	150.133	1800	28.440	84.670	111.125	122.370	126.340
600	43.000	64.900	79.500	89.016	101.238	1900	18.190	91.810	105.990	117.416	122.500
700	42.000	80.000	87.720	98.897	110.800	2000	15.714	61.950	90.250	85.330	100.870
800	28.840	90.990	116.770	126.690	133.280	2100	14.800	45.250	50.700	53.520	56.890
900	41.690	94.000	105.980	120.000	126.690	2200	17.150	77.590	80.540	82.500	87.000
1000	48.690	102.000	114.700	125.360	132.626	2300	19.260	64.500	114.730	117.630	122.290
1100	65.500	97.890	102.390	147.850	165.040	2400	80.000	96.610	98.125	104.200	113.440
1200	68.790	98.980	125.430	162.750	171.320	2500	55.670	71.230	78.740	125.550	162.610
1300	125.000	190.560	195.500	208.120	214.056						

Table 1. Flood extent in different period of time (1:30pm - 3:30pm)

From the data in the table, it can be seen that the flood extent increased quickly at every station in the West Creek channel. The nature of land cover and the steep/narrow channel led to this rise in the flood in the West Creek Catchment. Water began entering the channel at 1:30pm. From the DEM elevation, the minimum flood extent in stations across 1400m to 2300m, especially at station 2100m which was 14.800m. The maximum flood extent was 125.000m at station 1300m. The minimum and maximum extent at 2:00pm was 32.000m at station 1700m and 190.560m at station 1300m respectively. From the DEM it can be seen that the high elevations are at the 2100m station which experienced minimum flooding. The average flood extent from 2:30pm to 3:30pm was 50.700m, 53.520m and 56.890m respectively. Whereas the low elevations in station 1300m. The average flood extents for 2:30pm to 3:30pm were 195.500m, 208.120m and 214.056m respectively. Figure 9 shows clearly the minimum and maximum flood extents from station 100m to station 2500m. The minimum extent at the peak flow at 3:30pm at station 2100m was 56.890m. The maximum extent at the peak flow was 214.056m at station 1300m. The extent from Nearmap aerial photo is about 51.600m to 195.730m. That indicates that the obtained results are acceptable.

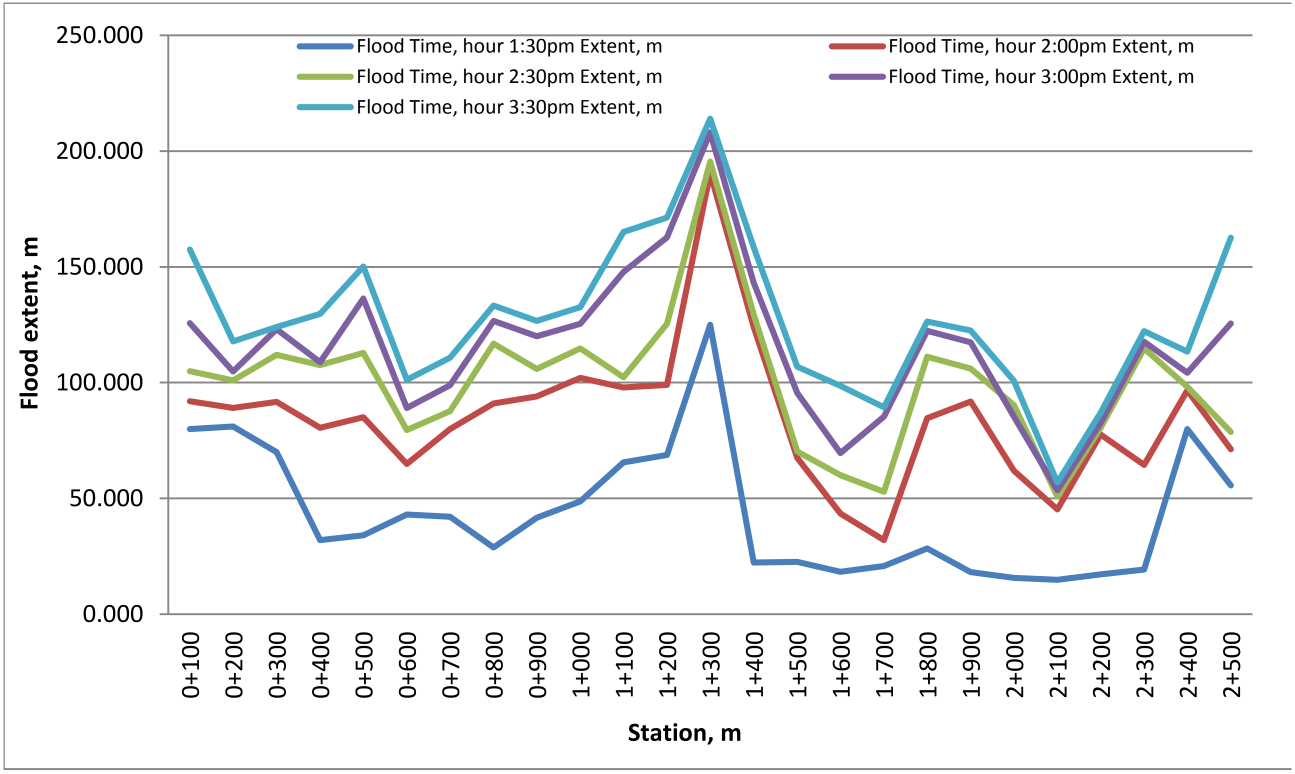
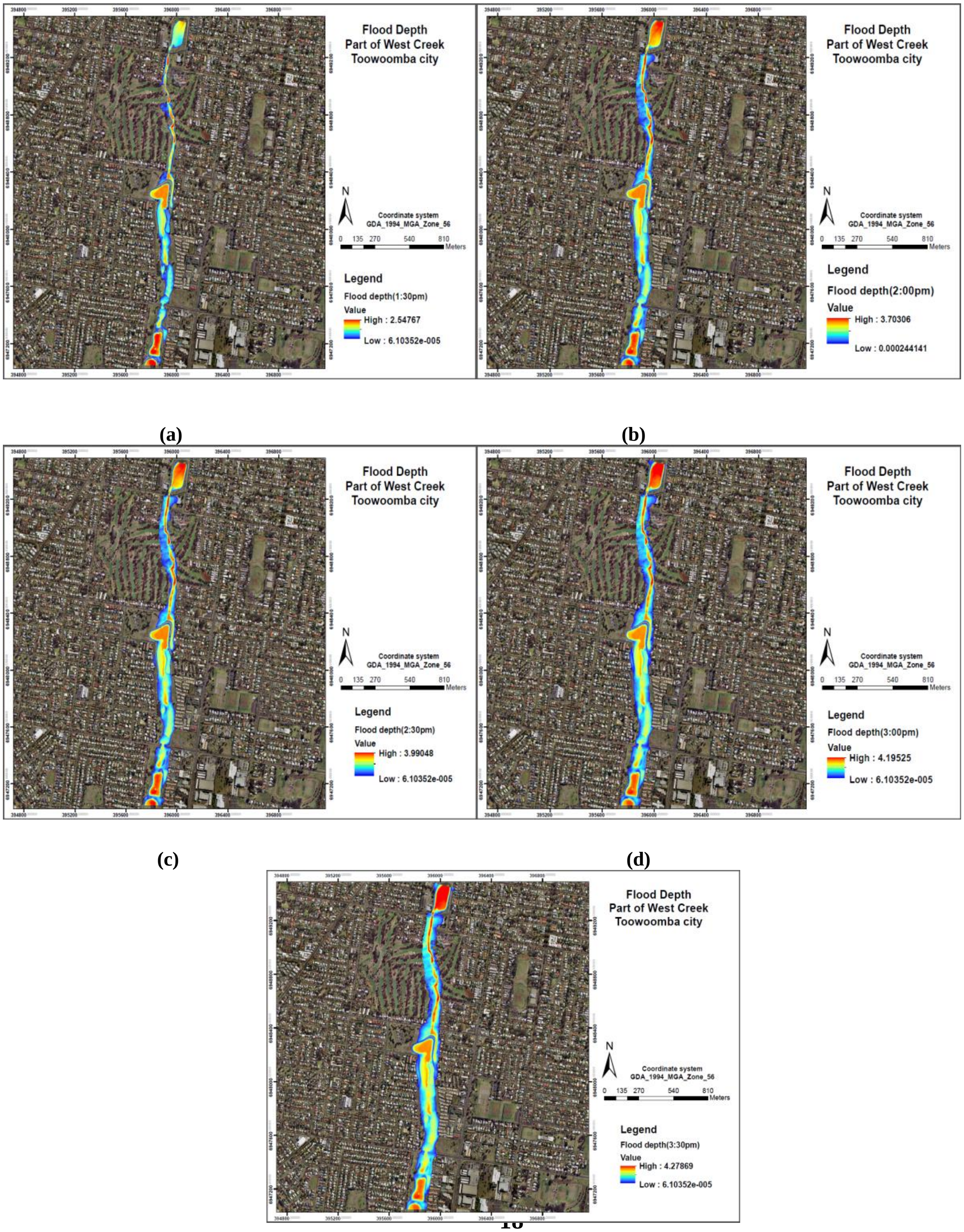


Figure 9. Flood extent, West Creek, Toowoomba on Monday 10 January 2011

The maximum flood depth in the study area was about 4.278m in the centre of the channel of West Creek. Figure 10 illustrates the flood depth in the West Creek.



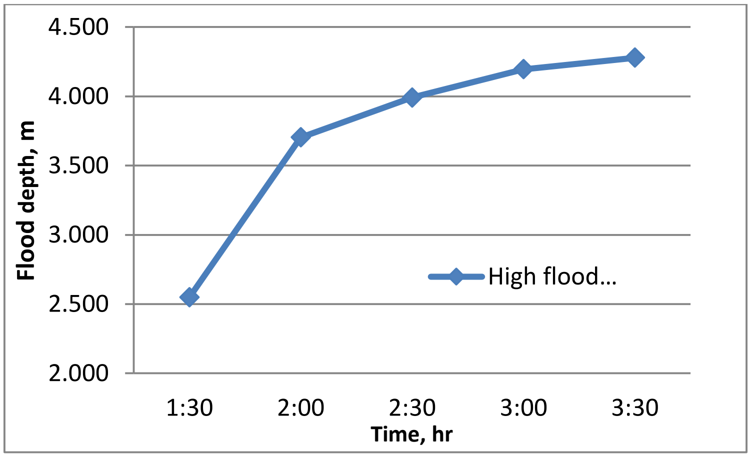
(a) **(b)**

(c) **(d)**

(e)

Figure 10(a-e). The flood depth in West Creek from 1:30pm-3:30pm.

It can be noticed that the model results gave a flood depth close to 2.547m at 1:30pm (see figure 10a). The flood depth from the Insurance Council of Australia Report was 3.670m at 2:00pm (ICA, 2011). The flow depth for this model was 3.703m at 2:00pm (see figure 10b). This gives an expected result in this research. The high flood depth occurred along the main channel and spread gradually to the floodplains. The West Creek Catchment has a lot of tributaries which contribute to high inflow into the main channel. Also, the channel flows in between slightly hilly terrain and the rain water in higher places flows rapidly into the main channel. This leads to a rising flood depth at 2:30pm, 3:00pm and 3:30pm to 3.990m, 4.195m and 4.278m respectively (see figures 10 c, d and e).



Time, hr	High flood depth, (m)	Low flood depth, (m)
1:30	2.547	0.041
2:00	3.703	0.041
2:30	3.990	0.041
3:00	4.195	0.041
3:30	4.278	0.041

Figure 11. Flood depth, West Creek, Toowoomba city on Monday 10 January 2011

Table 2. Flood depth

Table 2 shows the high and low flood depth between 1:30pm and 3:30pm. The depth increased from 2.547m at 1:30pm to 4.278m at 3:30pm.The intense rainfall began at 1:30pm. The flood depth was increasing rapidly at 2:00pm, rising from 2:00pm to 3:30pm, leading to a peak flood depth of 4.278m (see figure 11).

IV. Conclusion

With the potential of rising frequency and intensity of rainfall events as climate changes more, an increasing population, and the related land cover changes in the urban area, it is becoming important to develop models with reliable estimates that will help to reduce the effects of flash flood events, to assist emergency management and evacuation planning. Employing a hydraulic model and GIS have proved to be strong tools to produce maps of flood affected areas. The LiDAR data, high resolution remote sensing imagery and field survey improved the hydraulic model. The hydraulic model with reliable input data has the ability to create increasingly reliable flood inundation maps for the West Creek Catchment in the city Toowoomba.

Acknowledgments

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