

Numerical Modeling of Flood Vulnerability in Urban Catchments for Flood Forecasting

Amila P. Basnayaka, Ranjan Sarukkalige, and Induka Werellagama

Abstract—This study uses two of numerical modeling approaches to represent the urban catchment, and assess the flood risk of an urban catchment; hydrological surface routing approach and hydraulic 2D surface routing approach. Both approaches were combined with 1D hydraulic stormwater drainage network. XPSWMM was used as the modeling tool. This comparison leads to select most suitable approach to assess the possible flood inundations in the study area. Comparison of results of two approaches shows that the both approaches are suitable to represent urban catchment's hydrological behavior, but the results of hydrological surface routing are more close to observation data. Model was calibrated to one sub catchment and used to generate flood vulnerability maps for whole catchment. These maps will be used as water sensitive urban design guide lines in the future developments of the area, while structural and non structural measures are to be implemented.

Index Terms—Flooding, hydrological modeling, stormwater, urban environment

I. INTRODUCTION

Urban catchment hydrology needs more attention with the non riverine urban flood hazards. Such hazards are intensified by the rapid urbanization processes throughout the world, which are inevitable with the increasing population and the resource scarcity. These floods in urban environments have caused large societal and financial consequences with the majority of world population centralized to the urban cities [1]. Due to the higher costs of controlling flood drainage after land has been urbanized, reference [2] showed more efficient flood preventive control is possible by predicting the impacts from the potential urban developments, and planning control measures in early stages.

Numerical modeling is a widely used method of assessing urban hydrology and generates results for possible stormwater runoff hydrographs with the land-use variation due to potential urbanization; thereby predicting the possible flood hazards. There are number of models have been implemented in the history for the stormwater runoff quantity

analysis (e.g. SWMM [3]; Mouse [4]; Hydroworks [5]) and some are further developed as urban stormwater models [6]. Reference [7] and [8] cite that the representation of the urban hydrology within numerical hydrological models is done by many approaches throughout the recent history. With the inadequacy of common runoff catchment models and approaches to analyze the urban catchments with its complexities, combination of 1D and 2D models, different methods of representation of the urban concepts such as dual drainage systems [9], GIS and raster based flood modeling approaches by using LIDAR data and aerial photography (e.g. [1]; [10]; [11]) have been studied in the recent history.

Land use and land use management changes affect the hydrology, which will create the flood hazards [12]. Urban infrastructures such as roads, bridges, pavements and car parks, commercial and residential buildings, reduce the impervious area of the land and hinder infiltration, to increase the surface runoff. Also these paved surfaces together with urban drainage systems consisting of underground drains, manmade channels, manholes and gutters increase the rate of runoff through the drainage which demands comparatively large scaled stormwater management systems, and tends to flood the urban area, where no such facilities are provided [13]. Removal of vegetation cover for the urban land development reduces the evapo-transpiration, and leads stormwater to be retained in the surface for longer duration. All these changes of urban hydrology and their consequences of higher volume and increased peak flows within short durations cause the urban land to be inundated and affect the urban life and properties adversely.

This study is carried out to assess such growing urban catchment's drainage by modeling the urban hydrology within a numerical model. Two different approaches, 'hydrological approach' and 'hydraulic approach' have been considered to represent the urban hydrology. Basic difference of two approaches is the way they route the surface runoff. This comparison has been done based on the calibrated and verified modeling results for one sub catchment, where observation data is available. Then the most suitable approach to represent the urban characteristics of the area was selected and used to generate the critical duration flood inundation maps for the whole catchment.

The study area is being developing rapidly and current land sub division plans tend to further increase flood vulnerable areas by land use changes and newly man made drainages changing the natural hydrology. The results of this study will be used to assess the current stormwater drainage and predict possible flood vulnerable areas and flood depths, and to applying the local government's water sensitive urban design guide lines to future developments [14].

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II. APPLICATION OF HYDROLOGY AND HYDRAULIC APPROACHES

Three options within the software has been considered to model the urban floodplains and watercourses in the history [15]. They have recognized modeling the urban water courses and flood plains in 2D, urban watercourses and flood plains using a combination of 1D (watercourses), and 2D (floodplain) elements and urban drainage systems using a combination of 1D (piped drainage) and 2D (overland flow) elements. In most of the previous studies, the urban catchments were represented by giving modeling parameters like infiltration, surface roughness based on the impervious and pervious percentages. Then the surface routing was done by usual hydrological methods, which analyze the urban catchment as separate sub catchments according to given impervious and pervious conditions.

The Avenues sub catchment was considered to model for the calibration and verification purposes. It was modeled by using two separate approaches from above with a major difference of method used for the surface flow routing. In both cases pipe drainage network is modeled and surface runoff was combined to the drainage system through the manholes. First method was named as hydrological approach, which route the surface flow by using a hydrological method. The drainage network consisting of pipes and manholes was modeled as consequent 1D links and nodes network in hydraulics layer. As the hydraulic analytical engine, EXTRAN was used for the 1D flow simulation [16].The catchment is divided to small sub-catchments, and the flow from each sub catchment is routed to the pipe network through the adjacent manholes. Land-use types were calculated as percentages of the total sub-catchment areas, and given as separate sub-catchments for the appropriate nodes. Manning's roughness values for the surfaces were also assigned according to the land-use categories. Then the Laurenson method [17], integrated in the software was used for the surface runoff routing. The major Avenue basin was modeled as a reservoir in lined with 1D pipe network. The outflow boundary condition for the model was given as a fixed back water effect to match the existing tail water conditions. The water depth of tail end was taken by direct observations of particular rainfall scenario. The Initial water depths for the manholes and reservoir were assigned from the observation data. Finally the 2D hydraulics layer was used to count the excess water spilling out of over capacitated manholes. This was achieved by letting the boundary conditions of the manholes to be connected to the 2D network, so the excess water from manholes can flow in to the 2D network and again fill back to the manholes from the 2D network, as the pipe network has regained the capacity with the time. Infiltration values were given as zero for the 2D land-uses to prevent the double counting of the infiltration losses. Only the surface roughness values were given to 2D layer.

Some of the studies including [11],[15],[18] have presented the urban features in 2D network considering the features like road network and its components, open channels, detention basins and other water management structures, making the numerical model more similar to the physical urban hydrological cycle as much as possible. In the

hydraulic approach, surface runoff was modeled in the hydraulic layer using the XPSWMM 2D option. 6m x 6m grid size was used for the terrain. The digital terrain model was created by using the available LIDAR data. The coarseness of the available contour map was reduced to some extent manually by entering the elevation values for the road network, filled areas and ponds. The basin was modeled in the 2D network as a low elevated filling area, rather than a reservoir in the 1D hydraulic layer. It has given the initial water depth according to the observation data. The land-use types were defined according to the aerial map and values were assigned with infiltration capacities and roughness coefficients. Rainfall was given in to the 2D network, and the surface water routing was carried out by the 2D engine. The shallow water equation was used by the analytical engine to route the surface water simulation. Same as hydrological approach the water from 2D network link with the 1D network through the manholes. The excess water is represent as flooding as same as hydrological approach. Moreover in this approach the depth of surface-routed water is considered in the flood representation and also in the calculations. The flood inundation depth is simulated at the same time as surface flow is routed and the excess water from manholes flows back to 2D network. Absence of the fine topographical data to generate exact digital terrain model can cause this approach to be not accurate as anticipated.

Reference [18] mentioned strongest influences to the results are observed in the downstream part of the domain (due to cumulative effects) and in the streets filled by backwater effects at the downstream in their modelling work. In this study also the strongest influence to the results is backwater effect, which is changed with the time in the downstream. Also the results can be varied with the time steps and grid sizes used. Time step for the 2D model run was chosen as 4s by trial and error runs and avoiding the iteration errors giving negative flood depths.

In both cases Avenues sub catchment model for the calibration was given the input hydrographs from the adjacent two sub catchments, Industrial Area and Warten Lake. There were negligible amount of input from these two sub catchments to the Avenues model from the rainfalls which are considered to calibrate and verify the model, but they gave considerable input to the 1 in 100 year average recurrent interval, critical duration rainfall event. After the Avenues sub catchment model has been calibrated and verified, same parameters were applied to the total catchment. Hydrology method is selected and used to generate the flood inundation mapping to total catchment. Input hydrograph from the Avenues sub catchment model was given to the Main Drain sub catchment model. Natural channel existing in the Main Drain catchment was modeled as a 1D link with natural shape and given the surface roughness to the channel bed and banks.

III. THE STUDY AREA: CENTRAL CATCHMENT

The study area, Canning Vale Central catchment consist of about 248 ha in Canning Vale, which is a rapidly urbanizing area in Western Australia, situated about 25 km south to Perth. The Central catchment is having the features of

modern urban residential city with housing lots covered with roofs, paved front yards and drive ways, roads and footpaths, commercials buildings and car parks, public open spaces and water sensitive urban designs like swales, detention and retention basins, bio-pockets together with underground drainage system. It has been divided further to two major sub catchments named as Avenues sub catchment (AV) and Main Drain sub catchment (MD) to model them within the limitation of the software and to calibrate the model using the available observation data. Stormwater from Avenues sub catchment directly flows in to the Main Drain sub catchment after retaining part of it within the Avenues basin. In major rainfalls over about 1 in 5 year central catchment is having two main stormwater inflows from two other sub catchments Industrial Area (IA) further south west to it and Warten Lake sub catchment (WL) to the south. These inflows are limited to a design peak flow of 75l/s to conform with the local government limitations. In this study inputs from these catchments were counted by modeling them as separate catchments, because of their negligible amount of contribution to the Central catchment in lower rainfalls. The layout of sub catchments is given in Fig.1. The Avenues catchment is considered as a key guidance to the calibration and verification purposes of the model. There is a computerized data monitoring device fixed at Avenues basin's outlet to measure the flow data, basin water depth, rainfall and ground water level which were used to define boundary conditions and to calibrate the model. In the flood forecasting for major rainfall scenarios all inputs from Industrial Area and Warten Lakes together with Avenues catchment and Main Drain catchment was considered.

The Central catchment is bounded by Ranford Road to southwest, Campbell Road to southeast, Dumbarton Road to northeast and Washington terrace to northwest, with the total size of 36 hectares. It is basically with flat grades of 1:2000 approximately [19]. The land-use varies from industrial and residential to water logged swales, while about 75% of the catchment is residential and having lots with low permeable paved surface covering about 75% of a lot by building roofs and paved access ways. Some of the roofs were directly connected to the road's stormwater network while others were not yet connected. The average annual maximum ground water level in the catchment is within 0.5 – 0.7 m from surface, which is preventing the possibility of infiltration of runoff to the sub soil even in a small rainfall event. Overall Central catchment is having same features like Central catchment with its major difference of additional swales and natural channel. Digitized drainage system with GIS mapping exists for Central catchment. Underground pipe network connected to the surface level through manholes directly convey the storm water to the major basin called Avenue basin. From the basin there is an outlet connected to major drainage line, which carries excess water to the northeast of the catchment, while collecting all the inputs from Main Drain sub catchment as well. The aerial photo showing the land-use with exact coordinates and the 1m contour data is available to the whole catchment.

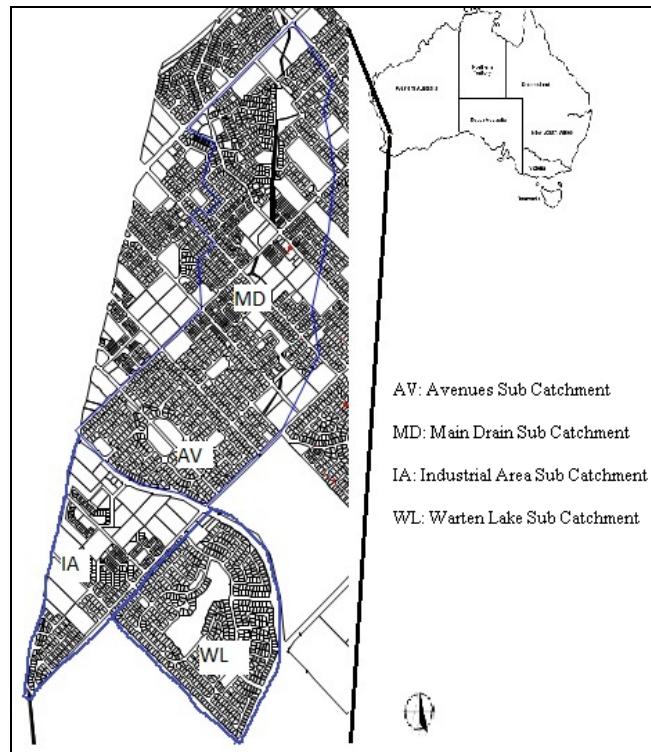


Fig. 1. Central Catchment with its sub catchments and adjacent sub catchments

IV. RESULTS AND DISCUSSIONS

A. Model Calibration and Verification

Calibration of the two approaches was carried out by using the observation data for the water depth of the Avenues basin for a 3 days rainfall event on 14th to 17th June 2010. The outflow backwater condition was one of the major parameters affecting the outflow from the catchment, hence the water depth of the basin. The outfall backwater depth was given from the observation data, and length of the outflow pipe was considered to be the length of the main drainage line, while neglecting the inputs to it. This has reduced the effect of change of tail water conditions to the model calibration parameters. Roughness coefficients, infiltration rates and groundwater inflow have been considered as sensitive catchment characteristics and used as calibration parameters. The roughness values and infiltration values used to calibrate the model are given in the Table. 1.

TABLE I: MANNING'S ROUGHNESS VALUES AND INFILTRATION RATES USED AFTER CALIBRATION

Land-Use Type	Manning's Roughness Value	Infiltration Rates	
		Initial/ (mm)	Continuous/ (mm/h)
Public open spaces and gardens	0.050	15.0	2.0
Roof	0.014	1.0	0.1
Ponds and swales	0.025	-	-
Roads	0.014	1.0	0.1
Car parks and other paved	0.025	1.0	0.1

The calibrated models' results for the water depths of the Avenue basin against time are shown in the Fig. 2. It shows

both approaches are capable in representing the hydrological behavior of the catchment. Hydrological approach is more accurate than hydraulic approach. The comparison was further analyzed by the graph of model results against observation data for hydrological approach in Fig. 3 and hydraulics approach in Fig. 4. This confirms hydrological approach is more accurate, having $R^2 = 0.855$, whereas R^2 for hydraulics approach is 0.5136.

Verification was done for another independent rainfall on 9th to 12th July 2010 and results are shown in Fig. 5. The results show the both approaches are appropriate to assess the urban hydrology. The modeled water levels of Avenues basin for both models have similar effect from fixed tail-water conditions, which is varying in the actual case.

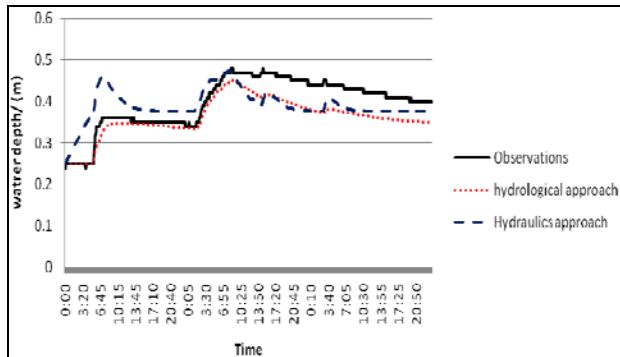


Fig. 2. Calibration of hydrological and hydraulics models (using the rainfall event 14th to 17th June 2010)

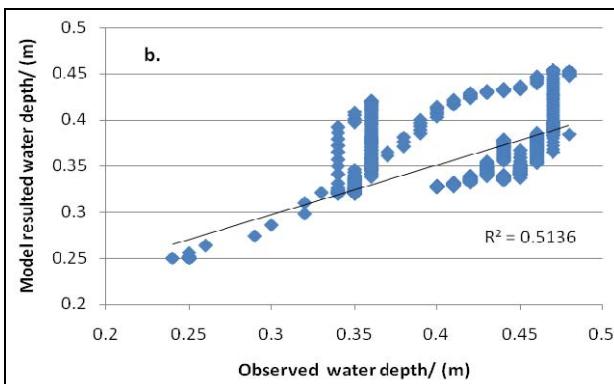


Fig. 3. Model results against observation data; hydrological approach

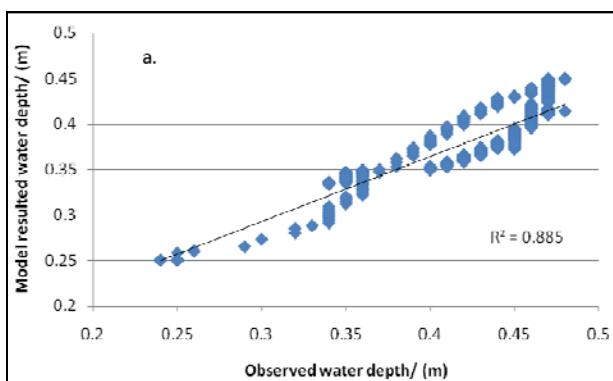


Fig. 4. Model results against observation data; hydraulics approach

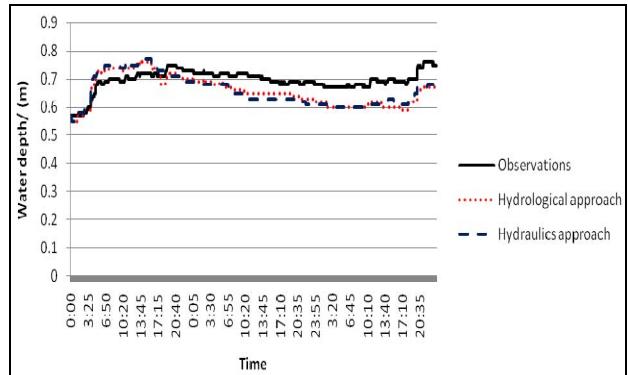


Fig. 5. Verification of hydrological and hydraulics models. (Using the rainfall event 9th to 12th July 2010)

B. Flood Vulnerability Mapping

The hydrological approach was selected to develop flood maps with its accuracy than the other approach. The rainfall scenarios of average recurrent intervals of 1 in 1 year, 1 in 5 year, 1 in 10 year and 1 in 100 year flood events were used to predict the possible flood areas and depths. The historical rainfall data were obtained from the intensity - frequency - duration curves [20]. Critical duration for this event was selected as 1 hour by running the model for 8 separate durations from 10 minutes to 3 days. The results for 1 in 100 year critical duration rainfall event are showing in the flood maps; Fig. 6 for Avenues sub catchment and Fig. 7 for Main Drain sub catchment. The results show the vulnerable area for 0.10 m to about 0.7 m flood depths in both maps. Water heights show above 0.7 m around Avenues basin because the basin was modeled in the 2D layer giving its current water level and can be neglected considering the basin capacity. Fig. 6 shows one more cluster of above 0.7m water depth northwest to the avenues catchment, which is again due to a basin, out of the catchment. Boundary condition was implemented in this area to count the water, without dissipating from the model and these water depths also can be neglected when deciding development guide lines using the results. Area flooded about 0.6m to west of the avenues basin is a public open space and having historical flood issues. In Fig. 7 area in the center of the map the flood depth is about 0.6m. This is along the natural channel, which carries inputs from Avenues sub catchment together with Main Drain sub catchment's water. In the historical records there have been flood issues along channel. Areas showing flood depths of about 0.24m are the swales and they are normally filled with water even for small rainfall events. The modeling process has a lag time, and the surface runoff which is routing through the hydrological layer will not simulate to calculate the flood depths until they flow back from manholes, but overall flood depth representation is adequate after comparing with the historical data. Further enhancement can be done by using the topographical contours with the contour gap of about 0.2 m, which is recommended by reference [16].

C. Flood control and Flood Management

Caning Vale Central Catchment is under rapid land developments due to sub division of the land lots, which will affect current hydrology of the area by changing the land use and land use management. The results of the study are very

useful for the local authorities in land development decision making and development of flood management strategies. This study gives possible flood vulnerable areas, and depths of flood that can occur. The areas identified as high risk of urban floods should be developed with adequate care, and water sensitive urban designs are to be implemented accordingly. The results of 1 in 5 year and 1 in 100 year average recurrent rainfall scenarios will be used to assess the current stormwater management drainage and 1 in 100 year scenario will be used to assess the adequacy of the road network in a major event.

Structural measures such as increasing drainage capacities, retaining 1 in 1 year event's stormwater within site, increasing landfills before further constructions, etc. can be implemented to prevent these non riverine urban floods. Further these results will lead to adaptive structural measures well integrated within the landscape promoting best management practice [21]. Non structural measures such as real-time forecasting and alert systems, information and training campaigns and tax adjustments can be implemented to the areas identified along the natural channel, which cannot be safeguarded by the cost effective structural measures [22].

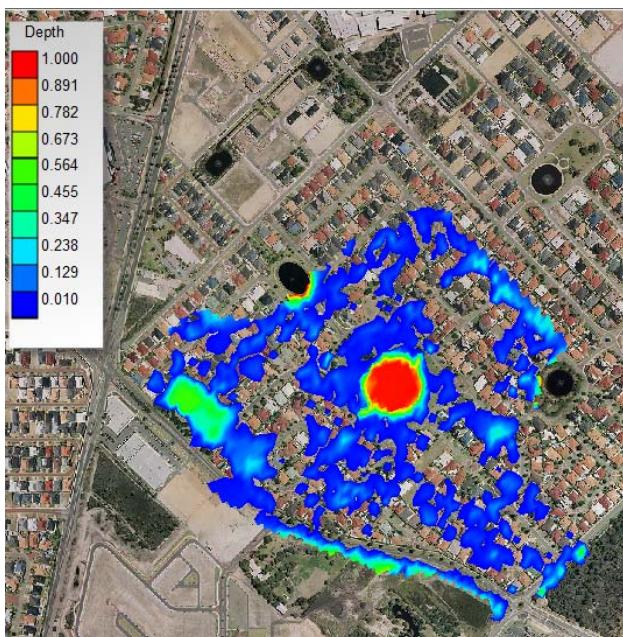


Fig. 6. Flood inundation mapping for 1 in 100 year critical duration flood event for Avenues sub catchment

V. CONCLUSION

The study used two approaches, hydrological approach and hydraulic approach to simulate the flood inundation of an urban catchment. The comparison was made on both approaches for their capability to represent an urban catchment more accurately. It is identified that both approaches are capable of representing the complex urban hydrological catchment together with 1D drainage network, but the coarseness of the topographical data might reduce the accuracy of the hydraulic approach. The results show that the hydrological approach is more accurate with the observation data having the $R^2 = 0.855$, whereas the hydraulic approach gives the results of $R^2 = 0.5136$ in the calibration process.

The most suitable approach to represent the study area's urban hydrology was selected as hydrological approach and whole catchment was modeled accordingly. Flood vulnerable maps for several average recurrent rainfall events were generated. These maps will be used to assess the current stormwater drainage and to decide the local government's urban storm water strategies and plans for the future land subdivisions and new developments.

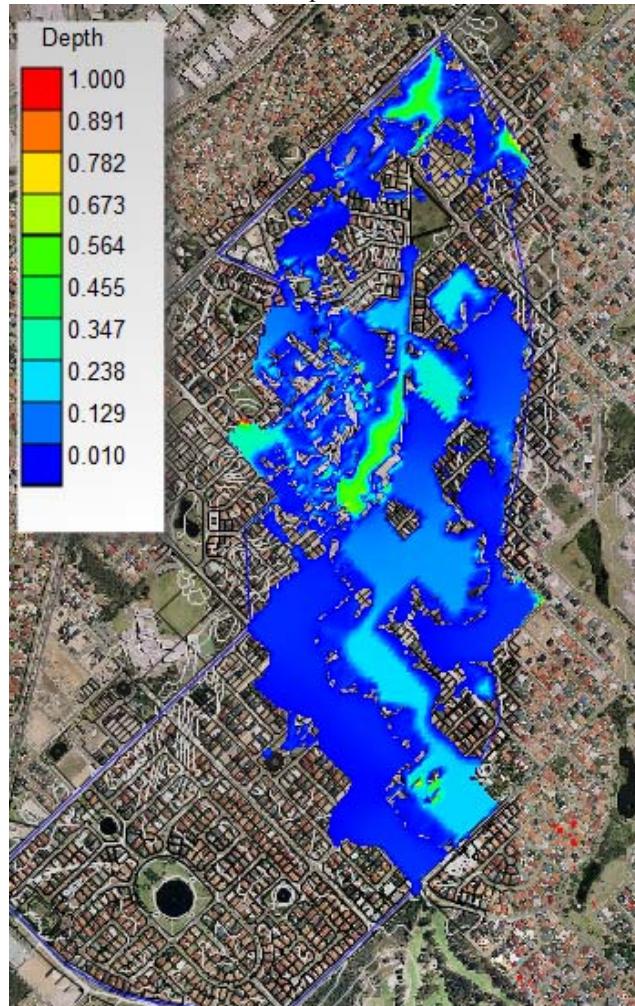


Fig. 7. Flood inundation mapping for 1 in 100 year critical duration flood event for Main Drain sub catchment.

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