ADDRESSING THE CHALLENGE OF WIDE-SCALE MODELLING OF OVERLAND FLOODING IN LIVERPOOL CITY COUNCIL

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Abstract: Events such as the 1998 Wollongong floods have clearly demonstrated that the threat to life and property from overland flooding can be just as significant as that posed by mainstream flooding. However, due to the small catchment sizes and low concentration times often involved in overland flooding, it can be a very complex problem to address. Notwithstanding, the 2005 NSW Floodplain Management Manual requires all Councils to address the risk posed from local overland flooding within their Local Government Area (LGA). Liverpool City Council (LCC) has resolved to help meet this obligation by commissioning the described study.

The study involved delineating 2 hectare subcatchments and flow paths throughout Council’s LGA based on Airborne Laser Survey (ALS) data. This level of catchment discretisation involved the delineation of over 10,000 subcatchments and 20,000 flow paths. As such, a highly automated terrain analysis approach was required. The CatchmentSIM software from the Catchment Modelling Toolkit (www.toolkit.net.au) was adopted for this purpose due to its accurate flow mapping algorithms and specialised approaches for urbanised catchments.

A key challenge for this study was to determine flood depths, damages and at-risk properties adjacent to the many thousands of identified flow paths. To address this problem, new algorithms were developed to extract and analyse cross-sections at each DEM cell and to apply customised hydrologic and hydraulic algorithms to determine depth, velocity and hazard values at the 5m cell size over the entire LGA. These values were then aggregated and analysed by subcatchment to determine high priority areas for further assessment.

Keywords: Overland Flooding, Overland Flow Path, Terrain Analysis, GIS, CatchmentSIM

Introduction (By Council)

The Liverpool Local Government Area (LGA) covers approximately 315m\(^2\) and is located in South West Sydney. The area has been earmarked by the State Government to be one of three major areas to support Sydney’s future expansion and has already experienced substantial growth in the last 20 years.

Liverpool City Council has completed several floodplain management plans for mainstream flooding in accordance with the NSW Government’s Floodplain Development Manual. While the mainstream flooding has been studied extensively within the LGA, little was known about overland flooding. The floodplain development manual requires all Councils to address local overland flooding within their Local Government Areas in the same manner as riverine flooding. Council is seeking to fulfill its responsibilities in regard to the policy by studying the overland flooding within its LGA and has commenced a 3 year rolling program.

The challenges in studying the entire Liverpool LGA are considerable. The area is very large with a large proportion being rural land. Council wanted to study the entire area (with the exclusion of Holsworthy Military base) without undertaking detailed studies into areas that have little overland flood risk. In early 2006 Council developed the brief for the study which outlined specific outcomes but didn’t specify the required approach. This enabled the consultants to propose the methodology and allowed for innovative approaches to be presented. Council commissioned stage 1 of its overland flooding project to investigate overland flooding over the entire
Broadly, the aim of this study was to identify overland flow paths, determine the risk they posed to properties and categorise the effected areas in terms of overland flood hazard. The areas identified in the stage 1 study would be used to determine where to focus detailed studies for stages 2 and 3 of the rolling program. This approach would enable Council to get the most value for money whilst gaining an understanding of the overland flooding risk over the entire LGA.

SMEC was awarded the project based on their comprehensive submission and detailed methodology that will be presented in this paper.

Key Challenges

Overland flooding typically results from high intensity rainfall on small catchments with low times of concentration. Despite consisting of relatively low peak runoff rates, these flows travel along non-established flow paths which can impact upon property. In such cases, even low depth 'sheet' flow can present significant water damage potential (which is typically not covered by insurers). In extreme cases, high velocity / low depth flows resulting from overland flooding can present risks to life. For example, in the Wollongong flash flooding of 1998 much of the damage and risk to persons occurred as a result of overland flooding rather than stream based flooding.

In light of these differences, an assessment of overland flooding risk requires a significant departure from traditional methods of analysis for floodplain risk assessment. Firstly, overland flooding can occur in almost any part of a catchment as apposed to a flood study where assessment is usually restricted to established channels. This presents a problem of magnitude, in the case of this project assessment of overland flooding risk requires assessment in the order of hundreds of thousands of flow paths and tens of thousands of subcatchments. It soon becomes apparent that traditional methods and models will be impractical and an automated and less computationally intensive (per flow path) method is required. Secondly, the critical duration of a storm that will produce overland flooding corresponding to a given recurrence interval (eg., 100 Year ARI) may vary significantly over the catchment. Thus, it is often overly conservative to model a single 100 year storm over the entire catchment, rather the critical 100 year storm should be derived uniquely for each area of analysis.

Overview of Methodology

The methodology developed for use in this project was based on utilising terrain analysis techniques to determine the parts of Liverpool LGA that are at greatest risk of overland flooding. Council’s highly detailed Airborne Laser Scanning (ALS) data was used to derive a series of raster Digital Elevation Models (DEMs) with a 5m metre resolution to cover 6 major catchments, namely, Nepean River (inc Duncan’s Creek), Cosgroves & Badgerys Creeks, South Creek, Kemps Creek, Cabramatta Creek (inc Hinchinbrook) and Georges River.

These DEMs were processed using the advanced terrain analysis package, CatchmentSIM in order to derive flow paths and subcatchments. Prior to mapping these hydrologic layers, the DEMs were hydrologically conditioned by removal of flat and pit cells and drainage enforcement over the catchments.

An investigation was undertaken into the best hydrologic and hydraulic algorithms for incorporation into the study. After careful consideration, CatchmentSIM was customised to incorporate hydrologic relationships based on Watershed Bounded Network Modelling (WBNM) and the LCC zoning layer. A comprehensive hydraulic procedure based on automated cross-section extraction and application of Manning’s formula was also incorporated into CatchmentSIM. These algorithms were applied to each catchment for both of the 20 year and 100 year ARI events, and depth and velocity mapping was produced.
Hazard categorisation was undertaken in accordance with the procedures documented in the Floodplain Management Manual (2001). To ascertain a better understanding of the specific hazard posed to structural property within the LGA, the hazard mapping was intersected with a rasterised development footprint database that was derived from the buildings subset layer of Council’s ALS data. Using the resulting property hazard data, we were able to thematically rank the subcatchments with respect to their cumulative hazard and thus determine priority subcatchments and regions for further analysis.

Software Choice

As outlined previously, Council’s ALS data was used to create highly detailed DEMs which were analysed using hydrologic raster terrain analysis methods. Most conventional GIS packages as well as some specialised terrain analysis software applications now include hydrologic algorithms to delineate subcatchments and identify flow paths including the leading ‘off the shelf’ packages MapInfo and ArcGIS. However, the capability of these applications is limited by several factors, the most important of which are:

- These packages use the D8 algorithm for flow mapping which has several known limitations for overland flow; and,
- Difficulties are often encountered in urban areas where dominate flow features including hydraulic structures are not well represented in the DEM.

CatchmentSIM was selected for use in this study since it overcomes these pitfalls by incorporating a more advanced flow path mapping algorithm and several specialist algorithms for use in urban areas. More information on CatchmentSIM can be found at www.toolkit.net.au/catchsim.

Detailed Methodology

The LGA was divided into 6 catchments with up to 6 million DEM cells in each catchment. ALS data was supplemented with NASA SRTM data outside LGA boundary. CatchmentSIM was used to produce 2 hectare flow paths and associated subcatchments over the entire LGA. These results are shown in Figure 1.
The results from the 2 hectare flow path mapping give an excellent indication of the flow path distribution over the Liverpool LGA and form the basis for the hydrologic and hydraulic modelling described in the following sections. However, for qualitative analysis purposes it was decided that it would be valuable to produce flow path mapping on a much finer scale. As such flow path maps were also produced for 1/8 hectare (1,250 m²) drainage areas. These are displayed overleaf in conjunction with the 2 hectare stream for the Prestons-Lurnea area in Figure 2. While not modelled from a hydraulic standpoint, visual interpretation of these flow paths in areas of concern gives a good understanding of the overland flow path distribution in the upper reaches of each subcatchment. For example, a simple analysis of whether the minor flow paths follow the road alignments or travel through housing lots facilitates a good indication of the overland flooding risk.
Hydrologic Modelling

Following the flow path analysis, the project called for hydrologic modelling using design storm principles. In a typical flood study, the area of hydraulic interest is only a small portion of the catchment. Thus, it is relatively straightforward to determine the critical duration design storm. However, in overland flooding, the area of hydraulic interest often covers most the drainage catchment. As such, the critical duration for the design storm may vary widely throughout the urbanised area. This issue may be overcome by analysing a full range of durations for each design storm and adopting the most severe result for each part of the catchment. However, since this study was a steady state analysis, we were able to develop a more precise technique.

CatchmentSIM produces a raster dataset which reports the upstream contributing area for every DEM cell within the analysis. Using this dataset it is possible to determine a unique peak flow measurement for every DEM cell based on the critical duration event for its specific catchment attributes. To do this, we used WBNM to construct a series of models representing catchments of various sizes, slopes and impervious proportions in order to develop several relationships for application in the hydrologic component of our methodology. These relationships fitted peak flow against catchment area for three development zone intensities as shown in Figure 3.
The hydrologic relationships depicted in Figure 3 were approximated by fitting polynomial curves to the WBNM modelling results. Figure 3 also displays the Probabilistic Rational Method which can be seen to fit between the low and medium development scenarios. Using these relationships, a unique peak flow for each DEM cell was determined based on the critical duration design storm tailored for its specific catchment parameters. These peak flow were used in the hydraulic modelling method described in the following section.

**Hydraulic Modelling**

After trials of a number of methods (including TIN intersection), it was decided to use a raster based hydraulic algorithm for the hydraulic modelling component of the study. CatchmentSIM was customised to extract cross sections from the raster DEM at each cell along a flow path and at 10 degree increments along curves, as depicted in Figure 4. Slope and area values were obtained from the subcatchment attributes and Manning’s calculations were applied at each DEM cell. The velocity and depth calculated for each inundated cell was recorded. This method has the advantage for avoiding any requirements for interpolation between cross sections and associated errors. Furthermore, since new cross-section(s) are generated at every cell along a flow path the new peak flow applicable to that cell can be included at every new cross-section. This results in a more even distribution of flow inputs into the flow path, as opposed to stepping up flows at each subcatchment outlet. This can make a significant difference in a study such as this one that is mainly concerned with small flows and relatively shallow flooding.
The cross-sections were initially generated at a width of 3 DEM cells on both sides of the flow path alignment. The cross-sections were widened if necessary based on the following criteria:

Once the iteration has reached closure and the correct water surface elevation has been determined, the algorithm will check to ensure that the left and right overbank elevations in the cross-section are higher than the calculated water surface. In many cases, the narrow initial cross-section will result in a surface water that is not constrained by left and right overbank elevations resulting in an excessively high water level (due to the invisible wall assumed by formula at ends of cross-section). This is demonstrated by the red cross-section in Figure 5. In this case the cross-section is widened by one DEM cell on both sides and the surface water level is re-calculated. This is repeated until the surface water level is constrained within left and right overbanks similarly to the green cross-section in Figure 5. This iterative procedure is undertaken since starting with a wide cross-section can result in excessive flow splitting as demonstrated in the orange cross-section in Figure 5. This method is designed to ensure the flow is not split between multiple channels and the potential of hydraulic structures such as kerb and gutter to constrain flow and avoid inundation of low-lying areas is recognised.
Once a water surface elevation is determined that is constrained by higher elevation left and right overbank areas, the inundated DEM cells covered by the cross-section are recorded along with the depth of inundation and velocity. Once the analysis is complete, CatchmentSIM produces raster datasets for depth and velocity for the entire project area.

This algorithm was used to determine depth and velocity mapping along each of the 2 hectare flow paths. A sample of these results for the Prestons-Lurnea Area is shown in Figure 6.

![Velocity Mapping for the Prestons-Lurnea Area](image)

**Figure 6: Velocity Mapping for the Prestons-Lurnea Area**

Following depth and velocity mapping, hazard result were calculated based on the Floodplain Management Manual (2001), as shown in Figure 7.
The depth, velocity and hazard mapping produced provide quantitative insight into the potential overland flooding risks across the Liverpool LGA. However, they do not distinguish between overland flooding that may threaten property as apposed to inundation of roadways, drainage structures or rural areas, which may be of less concern. To gain a better appreciation of the potential risk posed to building it is necessary to compare the model outputs with a property database or building / development footprint. Following this, estimation of flood damages may be undertaken.

This was achieved by intersecting the hazard mapping with a property layout layer derived from the ALS data. The property layout is shown in Figure 8.
Figure 8: Derived LCC LGA Property Footprint for the Prestons-Lurnea Area

The property footprint depicted in Figure 8 was intersected with the overland flooding results to determine where overland flooding will threaten property as apposed to relatively harmless inundation of vegetated or floodplain areas. These results are presented for the Prestons-Lurnea region in Figure 9.
An important component of the study was to prioritise the 2 hectare subcatchments for further assessment. As such, the subcatchments were spatially analysed to determine their cumulative hazard rating by summing the hazard index relating to all DEM cells they contained. The top 200 were determined and listed both a tabular format (Figure 10) and visually (Figure 11 – for Prestons-Lurnea).
### Table: Sample of Priority Subcatchment Table

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Subcatchment Number</th>
<th>Area (ha)</th>
<th>Slope (%)</th>
<th>Cumulative Hazard</th>
<th>Hazard Ranking</th>
<th>Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cabramatta Creek</td>
<td>554</td>
<td>9.02</td>
<td>1.26</td>
<td>431</td>
<td>1</td>
<td>Very High</td>
</tr>
<tr>
<td>Cabramatta Creek</td>
<td>263</td>
<td>19.50</td>
<td>1.59</td>
<td>277</td>
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<td>Very High</td>
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<tr>
<td>Cabramatta Creek</td>
<td>880</td>
<td>6.68</td>
<td>0.51</td>
<td>256</td>
<td>3</td>
<td>Very High</td>
</tr>
<tr>
<td>Cabramatta Creek</td>
<td>614</td>
<td>4.39</td>
<td>0.33</td>
<td>215</td>
<td>4</td>
<td>Very High</td>
</tr>
<tr>
<td>Cabramatta Creek</td>
<td>670</td>
<td>4.96</td>
<td>1.06</td>
<td>214</td>
<td>5</td>
<td>Very High</td>
</tr>
<tr>
<td>Cabramatta Creek</td>
<td>1137</td>
<td>6.50</td>
<td>2.32</td>
<td>194</td>
<td>6</td>
<td>Very High</td>
</tr>
<tr>
<td>Cabramatta Creek</td>
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<td>5.15</td>
<td>1.50</td>
<td>193</td>
<td>7</td>
<td>Very High</td>
</tr>
<tr>
<td>Cabramatta Creek</td>
<td>309</td>
<td>4.70</td>
<td>1.33</td>
<td>179</td>
<td>8</td>
<td>Very High</td>
</tr>
<tr>
<td>Cabramatta Creek</td>
<td>1486</td>
<td>3.89</td>
<td>1.38</td>
<td>168</td>
<td>9</td>
<td>Very High</td>
</tr>
<tr>
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<td>8.97</td>
<td>1.85</td>
<td>168</td>
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<td>Very High</td>
</tr>
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<td>1.61</td>
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<td>Very High</td>
</tr>
<tr>
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<td>2.97</td>
<td>1.75</td>
<td>162</td>
<td>12</td>
<td>Very High</td>
</tr>
<tr>
<td>Cabramatta Creek</td>
<td>1291</td>
<td>14.22</td>
<td>2.29</td>
<td>161</td>
<td>13</td>
<td>Very High</td>
</tr>
<tr>
<td>Georges River</td>
<td>1826</td>
<td>2.58</td>
<td>1.23</td>
<td>158</td>
<td>14</td>
<td>Very High</td>
</tr>
</tbody>
</table>

**Figure 10:** Sample of Priority Subcatchment Table

**Figure 11:** Priority Subcatchments for the Prestons-Lurnea Area
The distribution of the top 200 priority subcatchments across the Liverpool LGA is shown in Figure 12. As shown, the three main areas of concern can be clearly identified using this method.

**Figure 12: Distribution of Priority Subcatchments**

**Discussion**

These results have been highly useful for prioritisation of further studies into the overland flooding risk. Council has now commissioned a second stage of the project to look in detail at 3 of these areas using 2D hydraulic modelling techniques.

It is also interesting to use the results to compare different regions of the LGA. For example, we can look at two suburbs, Sadleir and Cecil Hills. These suburbs have been selected since one is relatively new (Cecil Hills) where one is an older suburb (Sadleir). It is worth noting that the introduction of Australian Rainfall and Runoff in 1987 occurred after Sadleir was developed yet prior to the development of Cecil Hills. Australian Rainfall and Runoff (1987) introduced the major/Minor approach to urban drainage. It required flows up the 100 year ARI to be contained by major drainage measures such as a roads or drainage reserves, and that the finished surface of all allotments adjacent to flow paths must be at least 300mm above the 100 year ARI flood level. Hence, such an analysis is of interest since it may offer some insight into whether the requirements of Australian Rainfall and Runoff have resulted in a suburb that is better designed from an overland flooding risk perspective.
The simplest approach to result interpretation involves looking at the derived major (2 hectare) and minor (1/8 hectare) flow paths in relation to the aerial photograph. The overland flow paths for these suburbs are depicted in Figure 13.

**Figure 13: Comparison of Suburbs – Flow Paths**
It can be seen in Figure 13 that the flow paths in the newer suburb of Cecil Hills follow the road network closely whereas the flow paths in the older Sadleir – Ashcroft region often leave established roadways and travel through property locations. This gives a quick indication that the Sadleir – Ashcroft has a higher overland flood risk.

The final element of analysis is to display the property hazard results and priority subcatchments. These results are displayed in Figure 14.
As shown in Figure 14, Cecil Hills suburb is not considered a high priority for further assessment. However, the Busby – Sadleir – Ashcroft area is covered by numerous priority subcatchments including several very high priority subcatchments.

This type of analysis clearly indicates any derived risk of overland flooding and provides strong evidence that recent planning and development controls are a beneficial technique for reducing the risk of overland flooding to the community.

**Council's Closing Comments**

*Council have been very pleased with the outcomes of this study. Checks against known problem areas and areas recently developed confirmed the accuracy of the outputs.*

*The work was completed in 5 months (from awarding the project to receiving the final report) which enabled Council time to review the results before developing the brief for stage 2 of the works. The results of this study were directly used to formulate stage 2 of the overland flow path study which will involve detailed 2D modelling of 3 areas that have the potential to have significant overland flood hazard.*

*The study is currently a draft document, has not been adopted by Council and has yet to be reviewed by Council’s Floodplain Management Committee. The study will be used by Council and the Committee to identify priority areas for further detailed study in accordance with the process set out in the Floodplain Development Manual. It is these detailed studies that will document the impact of local overland flooding on individual properties and recommend management measures.*