OVERLAND FLOW PATH MAPPING FOR THE WELLINGTON REGION

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ABSTRACT

Overland flow paths and depression areas have been mapped for 17 catchments in Wellington City. Overland flow paths represent the predicted path of stormwater as it flows over the topography. They can be mapped using specialist GIS software and LiDAR data.

In addition to delineating flow paths, the peak flow for the 1% Annual Exceedance Probability (AEP) rainfall event was estimated using a computer algorithm to implement the rational method. The peak flows (and associated parameters required to estimate the peak flow) were provided for each overland flow segment, providing useful spatial information that can be retrieved from GIS databases with the click of a button. As well as providing thematic mapping options, the estimation of flow also provides a method for categorising and assessing the risk to not just flooding but other hazards such as contaminant mobilisation.

KEYWORDS

Overland flow paths, stormwater, peak flow, spatial information

PRESENTER PROFILE

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1 INTRODUCTION

Overland flow paths represent the predicted path of stormwater as it flows over the topography while depression areas map the potential extent of stormwater ponding if the stormwater network is full or failure occurs within the network.

Many urban areas in New Zealand lack stormwater models, flood hazard mapping and catchment management plans, the latter of which is now a requirement being imposed by some Regional Councils. Mapping of overland flow paths and depression areas provide a useful planning tool and high level starting point for identifying potential flood risk areas where an existing detailed hydraulic model has not been completed. Furthermore overland flow paths can be overlaid onto geospatial layers to identify potential contaminant transport pathways, high hazard areas for flooding, assess the impacts of proposed developments and understand problem flooding areas.

Capacity Infrastructure Services Ltd (Capacity) sought to have overland flow paths and depression areas delineated for 17 Wellington City catchments (Figure 1). Of these catchments, 13 had no existing models, flood hazard maps or catchment management plans. The outputs of this work are intended to be utilised in the development of Integrated Catchment Management Plans (ICMPs) that Capacity is preparing on behalf of Wellington City Council and are required by the conditions associated with discharge consents granted by Greater Wellington Regional Council in 2011. Overland flow paths and depression areas were also seen as a useful planning tool to assist with stormwater assessments for new developments.

Figure 1: WCC catchments

The majority of the catchments encompass relatively steep urban areas that are likely to respond quickly to rainfall and generate significant stormwater volumes during design rainfall events. Land use in the area includes areas of bush, open grass fields, residential housing of varying densities, commercial and industrial areas and transport infrastructure including road and rail networks and Wellington Airport.

Overland flow paths and depression areas produced in this work did not incorporate above ground features (buildings, bridges etc.) and thus primarily represent the predicted path of stormwater as it flows over the topography. Due to the varying nature of land use type, terrain and asset criticality it was necessary to produce overland flow paths that could accurately and appropriately represent such paths and allow for presentation in a visually effective way.

A tool was created which based on catchment characteristics allowed calculation of an estimated peak flow which can be accessed at the click of a button. This tool allows attribute information to be interrogated for any overland flow path and thus can be used to gain an appreciation of the magnitude of stormwater passing through a particular area. The data presented is obtained from a high level analysis and as such should be considered indicative only, however it allows for relative thematic mapping of both overland flow paths and depression areas based on a particular attribute of interest.

2 DISCUSSION

2.1 METHODOLOGY

Overland flow paths and depression areas were delineated using the System for Automated Geoscientific Analysis (SAGA) GIS software in conjunction with LiDAR data and mapped using QGIS software.

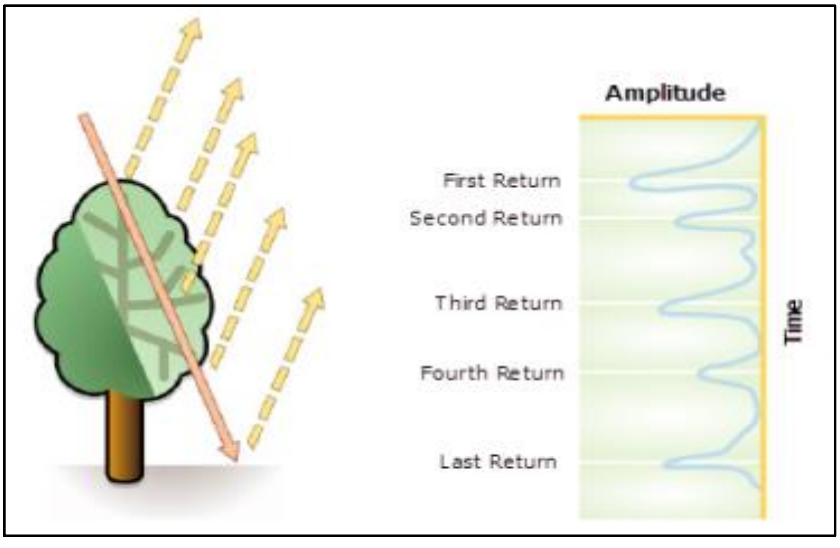
In order to produce OLFPs and depression areas the following information is required:

- A Digital Elevation Model (DEM), to determine the route of the overland flow paths;
- A sink drainage route detection grid;
- A catchment area grid.

2.1.1 DIGITAL ELEVATION MODEL

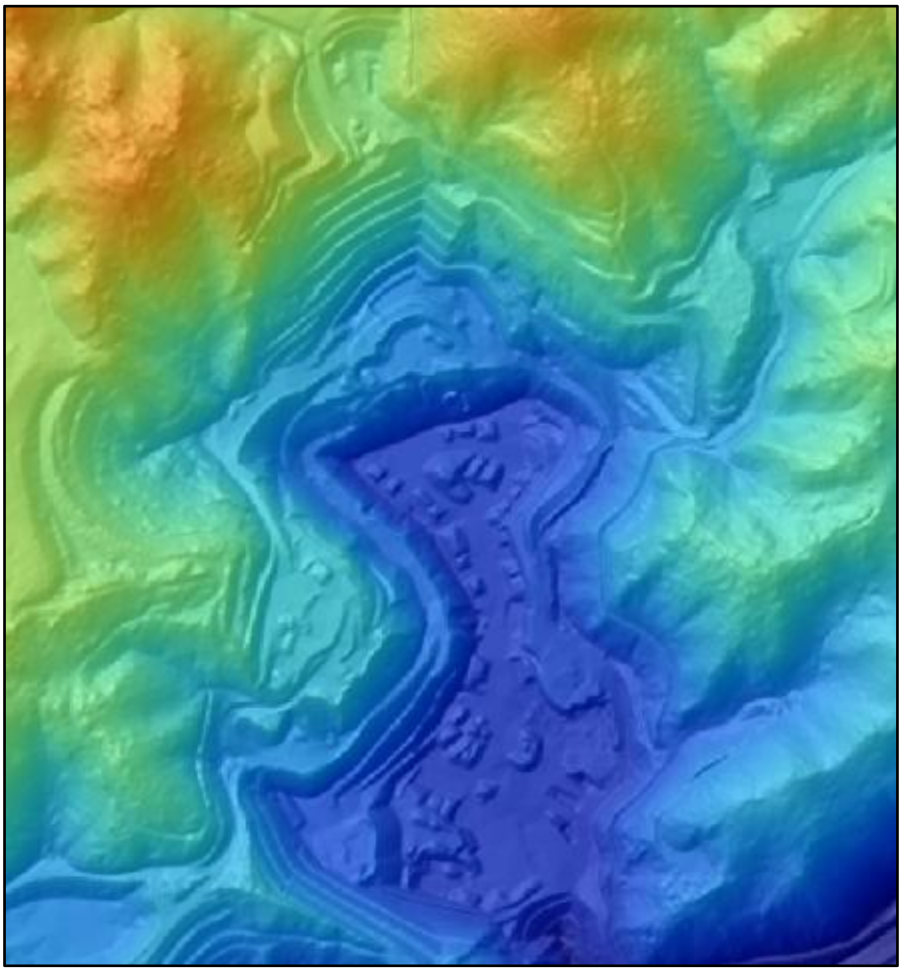
Overland flow paths require a DEM that is representative of the ground surface. This was obtained from LiDAR, a remote sensing technology that measures distance by illuminating a target with a laser and analysing the reflected light. LiDAR is typically recorded from an aircraft where the laser picks up multiple levels (deemed returns); the last return is usually taken to represent the ground surface (Figure 2). This return does not include building elevations, and above ground features are removed so as to not influence the topographical path of overland flow or ponding in depression areas.

Figure 2: Collection of LiDAR data



The Wellington City Council 2006 LiDAR dataset was obtained from the Koordinates website in order to extract the DEM (Figure 3). Due to this dataset not stretching to the full extent of catchment boundaries a section of the New Zealand School of Surveying 15m DEM was stitched onto the Wellington City LiDAR so the full extent of the catchments were included.

Figure 3: Example of DEM

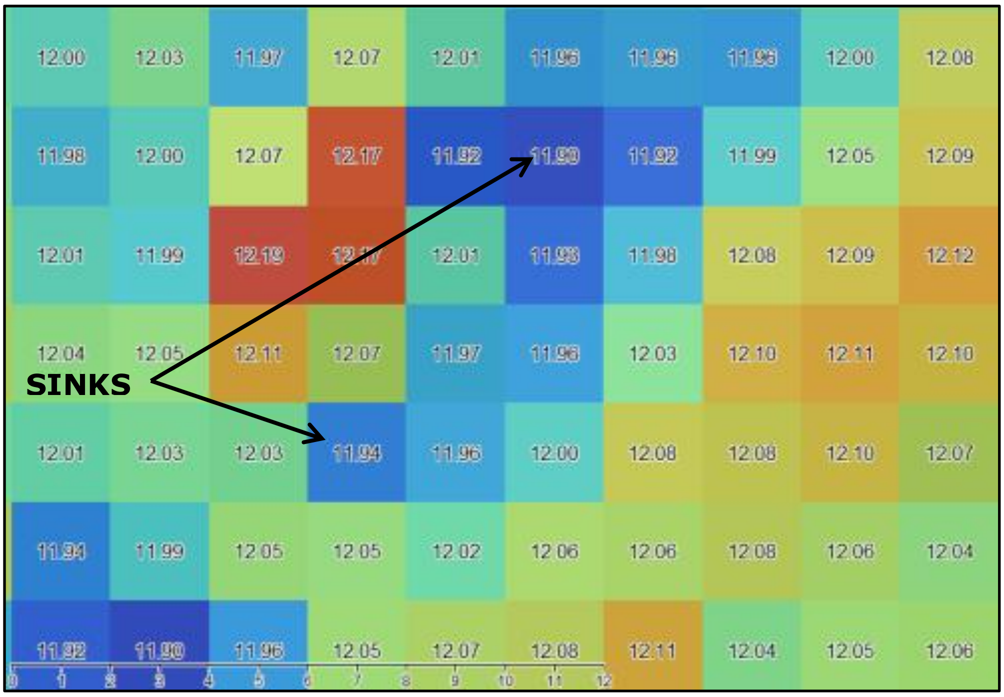


Depression areas in the DEM are identified and filled using the SAGA module Terrain Analysis – Preprocessing: Fill Sinks (Wang & Liu) (Wichmann, 2007), which uses an algorithm devised by Wang & Liu (2006).

2.1.2 SINK DRAINAGE ROUTE DETECTION GRID

The sink drainage detection grid was created in SAGA using the Terrain Analysis – Preprocessing: Sink Drainage Route Detection module (Conrad, 2001), with the DEM as an input. Sinks are defined as areas that cannot drain to anywhere, i.e. they are surrounded by topography with higher elevations (Figure 4). This can be problematic when determining an overland flow path as there is no obvious route for the cell to drain to. A sink drainage route detection grid identifies the best cell to drain to; generally this is the lowest adjacent cell. However, the path of the least uphill resistance is taken; therefore a higher adjacent cell may be moved to if this subsequently leads to the lowest local relief point.

Figure 4: Example of sinks. The cell number represents the elevation of each cell.



12.00	12.03	11.97	12.07	12.01	11.96	11.96	11.96	12.00	12.08
11.98	12.00	12.07	12.17	11.92	11.90	11.92	11.99	12.05	12.09
12.01	11.99	12.19	12.17	12.01	11.93	11.98	12.08	12.09	12.12
12.04	12.05	12.11	12.07	11.97	11.96	12.03	12.10	12.11	12.10
12.01	12.03	12.03	11.94	11.96	12.00	12.08	12.08	12.10	12.07
11.94	11.99	12.05	12.05	12.02	12.06	12.06	12.08	12.06	12.04
11.92	11.90	11.96	12.05	12.07	12.08	12.11	12.04	12.05	12.06

2.1.3 CATCHMENT AREA GRID

A catchment area grid contains the upstream catchment area for every grid cell. This was used to determine when a flow path should be initiated. This grid was created using the SAGA module Terrain Analysis – Hydrology: Catchment Area (Parallel) (Conrad, 2001). This module uses parallel processing of cells for calculation of flow accumulation and related parameters moving down a catchment by means of the Deterministic 8 method (O'Callaghan and Mark, 1984). A DEM is produced downwards from the highest to the lowest cell in a catchment, moving to the lowest adjacent cell with each step. Typically, a flow path will be initiated when a certain catchment area (and therefore flow) is exceeded.

The minimum contributing catchment area (threshold area) required to generate a peak flow of 100 L/s during a 1% Annual Exceedance Probability (AEP) rainfall event was calculated and used as a basis for displaying OLFPs for each catchment. This was achieved by solving for area using the basic rational method as shown in Equation 1:

$Q = CiA/(3.6 \times 10^6)$ (1)

Where Q is the flow rate (m^3/s), C is the runoff coefficient, i is the rainfall intensity (mm/hr) and A is the contributing catchment area (m^2).

Runoff coefficients were delineated for the entire Wellington City Council Region by classifying areas based on the area types specified in the Regional Standard for Water Services (Capacity, 2012). A weighted runoff coefficient was defined for each catchment using the percentage area of each land use type.

Analysis of the time of concentration for each catchment was undertaken to determine the appropriate rainfall duration to use. The Ramser Kirpich formula for time of concentration for overland flow was used as this method provided the best correlation to detailed analysis of catchment peak flow outputs from models provided by Capacity, and is shown in Equation 2 (Maidment, 1993):

$T_C = 0.0195\ L^{0.77}\ S^{-0.385}$ (2)

Where T_c is the time of concentration for overland flow (min), L is the maximum channel length (m) and S is the slope (m/m). The channel length was measured from delineated catchment boundaries and an average representative slope was taken over this distance.

The catchments were sorted into categories of threshold area required to generate the 100 L/s peak flow. These categories were:

- 0.75 hectares;
- 1 hectare; and,
- 1.25 hectares.

2.1.4 DEPRESSION AREA MAPPING

Depression areas were created by taking the difference between the sink filled DEM and the original DEM. Volumes, areas, maximum depths and the reduced level of the potential maximum water level of the depression areas were calculated. Mapped depression areas had to satisfy all of the following criteria:

- Area exceeding 500 m²;
- Volume exceeding 50 m³; and,
- Maximum depth exceeding 150 mm

The above criteria remove small depressions or 'puddles' that may not pose a risk or be relevant for the intended use of the depression areas. The depth criterion was set to 150 mm as this was seen as an appropriate depth for mobilisation of contaminants. In the case of identifying potential property inundation, a 300 mm minimum depth criterion is often used to account for the fact that floor levels are typically at least 300 mm above ground.

It is worth noting that this methodology does not identify whether the depression areas will fill. It is likely that some depressions areas are too large to fill even during a 1% AEP rainfall event. Areas of note are Kilbirnie and the Miramar/Strathmore area.

2.1.5 VALIDATION OF DATA

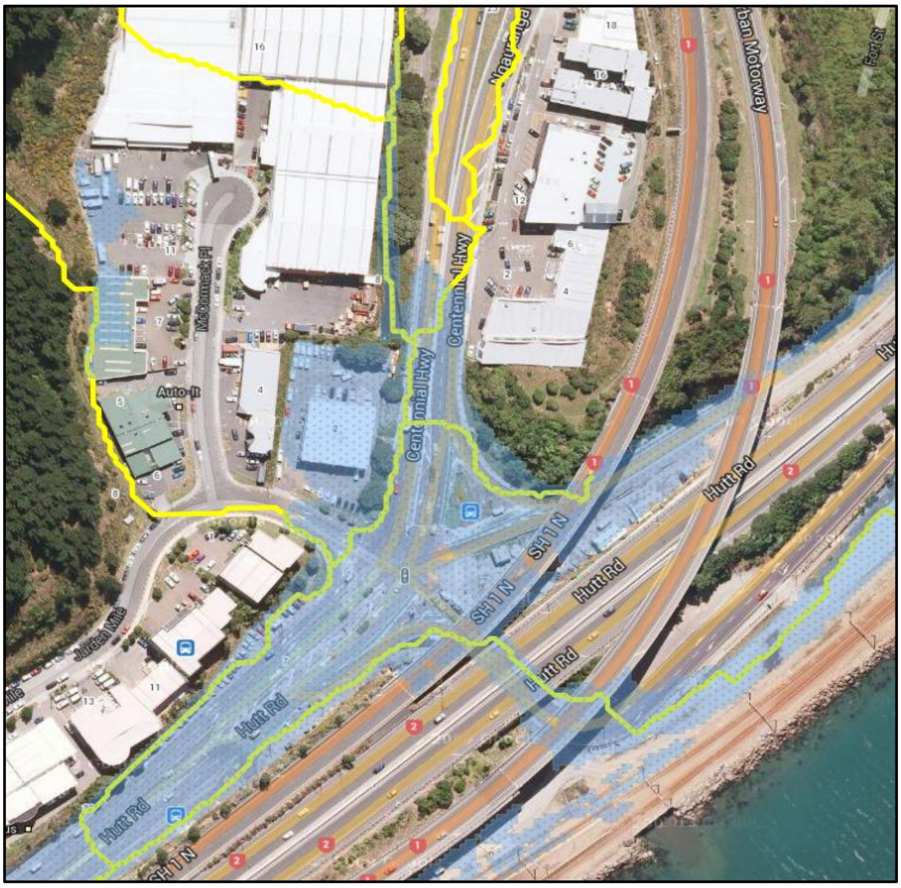
Overland flow paths and depression areas were validated against aerial photos, LiDAR and site inspections to ensure that each path correctly followed land contours and was not affected by unusual features picked up in the LiDAR. The process involved following each overland flow path and ensuring that the height of a successive cell in the direction of flow was lower than the current cell and also the lowest of all downstream adjacent cells. Aerial photographs were also examined to ensure overland flow paths were realistic and were not influenced by above ground features such as bridges and motorway flyovers. Site visits were undertaken to confirm flow paths in unusual/complex areas such as the Wellington Cable Car Tunnel and the flyovers through the CBD. The stormwater reticulation system was not included in any of the calculations undertaken as part of this project and thus changes were not made to account for stormwater conveyance via pipe networks.

Manual modifications were made to the LiDAR to remove the Hutt Road, SH1 N and railway bridges which were acting as a barrier to overland flow paths over the Kaiwharawhara Stream. This stream is the main drainage path of the Kaiwharawhara catchment into Wellington harbour and thus the bridges were seen as causing a direct interference with the natural path of overland flow. Other such issues arise from over-bridges and tunnels. Each cell in a DEM can only contain overland flow paths at one height and thus the removal of above ground features can result in overland flow paths being produced that are not technically correct if infrastructure was in place. This can be beneficial as overland flow paths are often used to identify which assets are in flood hazard areas. However in some instances this may not be desirable and it is necessary to address overland flow paths on a case by case basis relating to the intended purpose of the overland flow path and depression areas.

2.2 TOOL DEVELOPMENT

To enhance the usefulness of the mapped overland flow paths a tool was created which provides spatial information relevant to each flow path which can be retrieved from GIS databases with the click of a button.

Figure 5: Example of overland flow path and depression area mapping



This was achieved by developing a computer algorithm to estimate peak flows using the rational method. For each segment of an overland flow path, an associated flow was estimated for the 1% AEP rainfall event. The runoff coefficient for each segment of flow path was calculated using a weighted average to account for all the different runoff coefficients associated with the upstream area of a segment. The rainfall intensity was based on the Ramser Kirpich formula as described above. It should be noted that the time of concentration is calculated from the highest point of elevation for a catchment. This generally provides the highest time of concentration for a given overland flow path. However, there are some cases where an alternative route provides the highest time of concentration and the downstream segment will not account for this. The area was simply obtained from the catchment area grid (Section 2.1.3).

The attribute table keys for overland flow path and depression areas are shown in Tables 1 and 2.

Table 1: Overland flow path attribute table key

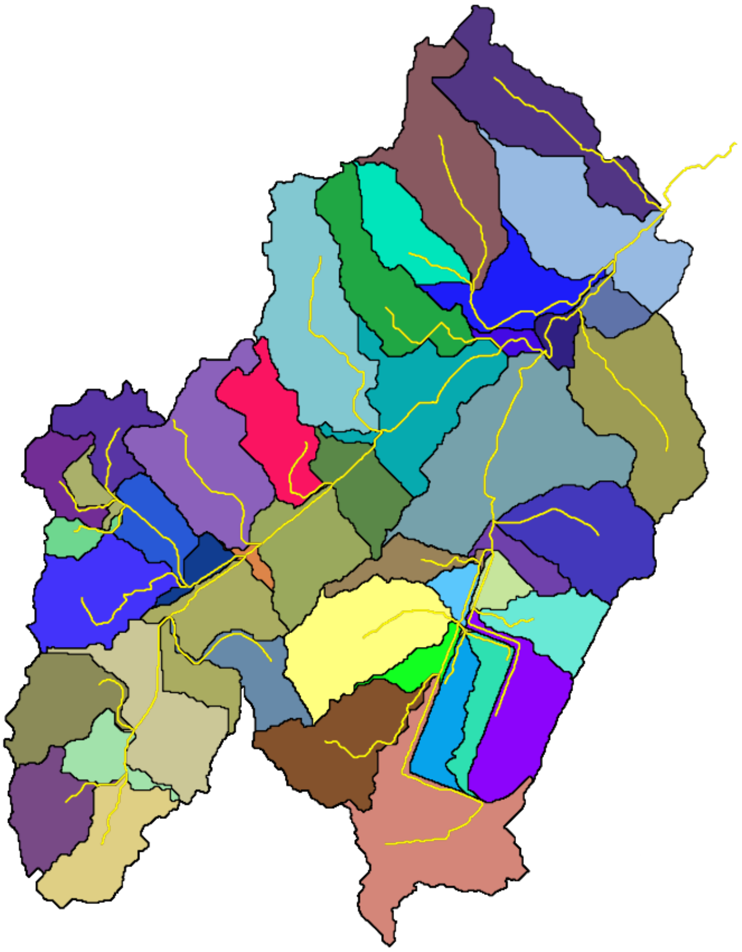
Overland Flow Path Attribute Table Key	
Order	The Strahler Stream Order Number
Peak_Q	Peak flow as calculated using Equation 1 (m^3/s)
Intensity	The intensity of the 1% AEP rainfall event (mm/hr)
Tc	Time of concentration (min)
Area_Max	The contributing catchment area at the vertex just upstream of the downstream confluence (m^2)
Area_Min	The contributing catchment area at the upstream confluence (m^2)
Length	The length of the segment (m)
Cum_Length	The maximum upstream length of the channel to this segment (m)
Weighted_C	The weighted runoff coefficient of the contributing catchment up unto this segment
Runoff_C	The runoff coefficient of the area the segment is located in
x_dist	The straight line length to the catchment head (m)
El_Max	The upstream elevation of the segment (m above datum)
El_Min	The downstream elevation of the segment (m above datum)
ElCum_Max	The elevation at the head of the catchment (m above datum)
X_Cord_US	The X Coordinate of the vertex at the catchment head
Y_Cord_US	The Y Coordinate of the vertex at the catchment head
X_Cord_A	The X Coordinate of the upstream (first) vertex
X_Cord_Z	The X Coordinate of the downstream (last) vertex
Y_Cord_A	The Y Coordinate of the upstream (first) vertex
Y_Cord_Z	The Y Coordinate of the downstream (last) vertex
X_2	The X Coordinate of the second to last vertex
Y_2	The Y Coordinate of the second to last vertex

Table 2: Depression area attribute table key

Depression Area Attribute Table Key	
Depth	Depth of depression (m)
Area	Area of depression (m^2)
Volume	Volume of depression (m^3)
RL	Reduced level of depression surface (m above datum)
Perimeter	Perimeter of depression area (m)

Following discussion with Capacity further development of this tool was made to incorporate a feature which identifies the contributing catchment for each flow path that is selected. At present this feature has not been implemented but an example of the results have been presented for the Northern CBD catchment as shown in Figure 6.

Figure 6: Identification of contributing catchment



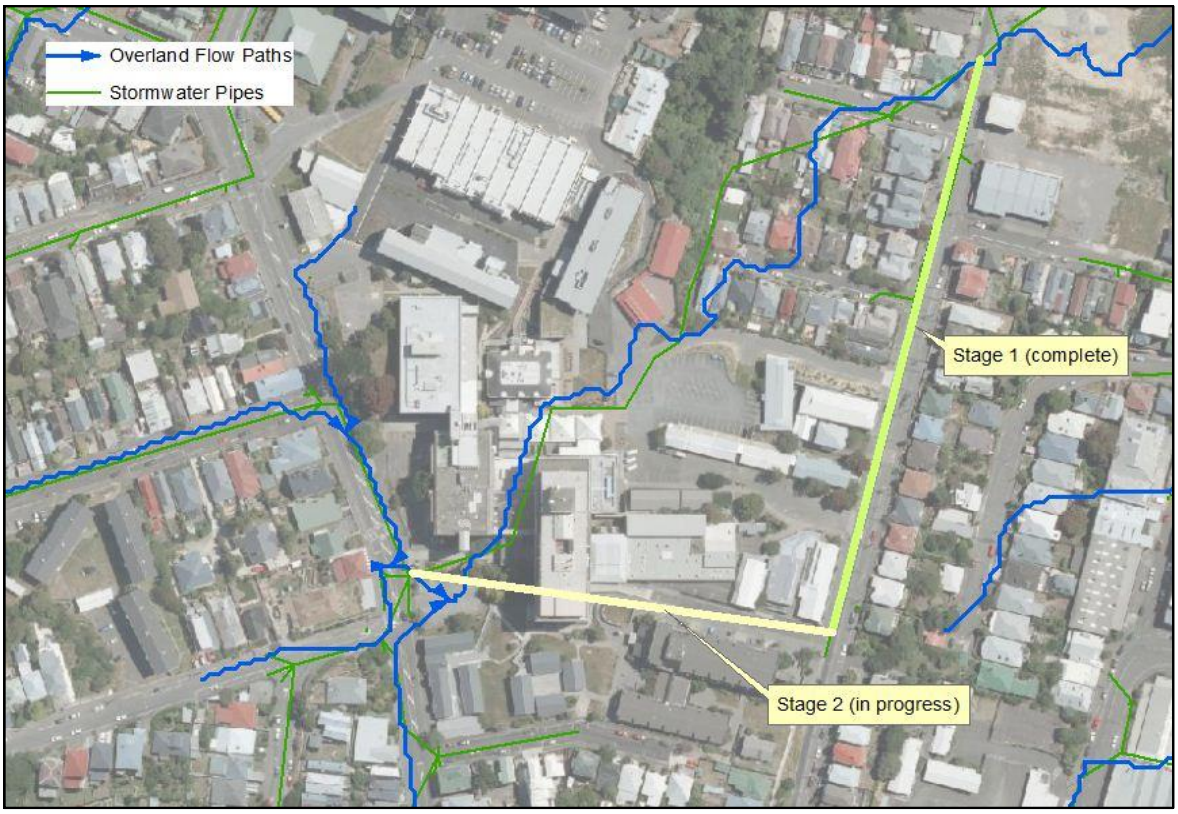
2.3 VERIFICATION

On the 6th May 2013 Wellington City was hit by heavy rainfall, estimated to have had an Annual Exceedence Probability (AEP) of approximately 5%. The storm exceeded the design capacity of much of the city's stormwater network, resulting in significant flooding in a number of areas. Many locations worst affected by flooding were in depression areas or in overland flowpaths.

Photograph 1 shows flooding at the entrance to Massey University on the 6th May 2013. Figure 7 shows the mapped overland flow path, which Photograph 1 verifies was activated on the 6th May when rainfall exceeded the design capacity of the stormwater system. Capacity is currently completing a staged upgrade of the stormwater network through Massey University which will increase the level of flood protection to 1% AEP.

Photograph 1: Entrance to Massey University, 6th May 2013 (taken by Emma Ward, retrieved from www.3news.co.nz)

Figure 7: Overland flow path through Massey University



Photograph 2 shows flooding at the corner of Adelaide Road and Rugby Street and Photograph 3 shows flooding in the Basin Reserve on the 6th May 2013. Figure 8 shows the mapped depression areas, which Photographs 2 and 3 verify were activated when rainfall exceeded the capacity of the stormwater system. Capacity is currently investigating upgrade options to mitigate flooding in this area.

Photograph 2: Flooding at the corner of Adelaide Road and Rugby Street, 6th May 2013 (taken by Alan @phantomobot, retrieved from www.twitter.com)

Photograph 3: Flooding in the Basin Reserve, 6th May 2013 (taken by Michael Ricketts, retrieved from www.nzherald.co.nz)

Figure 8: Depression areas around the Basin Reserve

2.4 PRACTICAL IMPLICATIONS AND FUTURE ENHANCEMENTS

Overland flow paths and depression areas provide many useful practical implications for stormwater management, both as a standalone feature and in conjunction with other tools. They provide decision makers with a basis from which to prioritise catchments for detailed hydraulic modelling and flood hazard mapping whilst also allowing quick approximation of flows and catchment areas. This can provide a useful check of existing catchment delineations, however it needs to be considered that overland flow paths only show the topographical catchments which may vary from catchments defined by the stormwater network.

Investigations into the causes of flooding incidences can be assisted by overland flow paths and depression areas, which can be used in conjunction with other tools to help aid emergency response by identifying where flooding may occur and the source of this flooding to better define response plans and high hazard areas. More effective emergency responses may prove significant following an extreme event such as a major earthquake, where initial inspections can be targeted at assets where there isn’t an adequate secondary flow path or which drain a significant depression area.

Defining stormwater assets associated with major overland flow paths or depression areas allows more effective ranking of asset criticality. A prominent example is the Wellington suburb of Miramar which was identified to be almost entirely contained within a depression area. Stormwater is drained by the Miramar outfall which runs beneath a man-made cutting through the hillside between Miramar Avenue and Cobham Drive. Depression mapping allows failure of the Miramar outfall to be associated with the potential flooding of the suburb by over a metre. This potential became a reality in 1929, when blockage of the outfall caused extensive flooding in the suburb as stormwater had no secondary means of draining from the basin.

Overlaying mapped overland flow paths and depression areas on to geospatial layers of sensitive sites allows identification of which of these sites are intersected by overland flow paths or are situated in depression areas potentially subject to ponding. This highlights sites from which a more detailed assessment may be necessary to determine the likelihood of these features contributing contaminants to the stormwater system and the potential transport pathways of these contaminants. Mapped depression areas also prove useful alongside overland flow paths. When assessing the likelihood of these features transporting contaminants into the stormwater system, a depression area in isolation may not be seen as an effective contaminant pathway. Conversely an overland flow path skirting the boundary of a sensitive site may not pose a large risk of picking up contaminants. However as can been seen in Figure 9 the depression areas can cover a larger portion of the site and have the potential to mobilise contaminants which may then be transported by the intersecting overland flow path.

Figure 9: Overland flow path and depression area intersecting a site

In order to maintain the accuracy of OLFPs and depression areas, it would be beneficial to update the results when more recent LiDAR data is available. The LiDAR data used in this study was flown in 2006 and has an error of 0.5 m in the vertical plane. A new DTM from LiDAR data flown in 2013 is being updated at present and it is expected that more accurate flow paths and depression areas could be obtained if this updated data is made available for analysis.

The inclusion of a greater range of flows corresponding to various design storm events was identified to be a useful enhancement of the tool. There is potential for this methodology to incorporate the stormwater network so that the upstream area and a quick estimate of likely ultimate peak flows (assuming no upstream restrictions) can be identified at any point in the stormwater network. This would provide a starting point for investigations and a check on manual flow calculations.

As part of Stage 1 of the Integrated Catchment Management Plans, Capacity have utilised depression areas as a high level starting point for identifying potential flood risk areas where existing detailed hydraulic modelling is not available. The outputs have highlighted a number of locations where there are critical assets such as tunnels or large culverts under embankments that aren't recorded in WCC's asset management system in sufficient detail, or at all.

Outputs have also been used to identify areas where further detailed analysis will be required as part of Stage 2 of the ICMP project. Overland flow paths and depression areas can help to determine whether a detailed catchment hydraulic model is required, or if localised capacity analysis for critical infrastructure is sufficient. Overland flow paths and depression areas, coupled with flow attributes, may also be used in Stage 2 of the Integrated Catchment Management Plans for catchments where detailed hydraulic analysis is not required or to supplement information provided by hydraulic models.

Overland flow path and depression mapping has also been used by Capacity for assessing the impacts of proposed developments and for investigating problem flooding areas. The outputs provide a basic understanding of the catchment layout and potential issues, which can then be refined by manual checks of LiDAR levels, site photographs and site visits.

3 CONCLUSIONS

Mapped overland flow paths and depression areas lead to better decision making in catchment planning and assessments of potential development. Furthermore attributing each OLFP and depression area and allowing these attributes to be accessed readily via a GIS interface provides for more effective use of outputs including thematic mapping options and quick, high level analysis.

ACKNOWLEDGEMENTS

The authors would like to acknowledge Capacity Infrastructure Service Limited for their permission and assistance with compiling this paper. Wellington City Council funded the project as part of the development of Integrated Catchment Management Plans: Stage 1.

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