Modelling An Overland Water Flow Path In An Urban Catchment Using GIS

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Abstract

It is difficult to account for urban drainage networks when modelling overland water flow in an urban setting using conventional GIS software. This paper presents a GIS-based method for incorporating subsurface drainage flow through conventional drainage networks into overland flow paths. Planners and engineers in local government can use our flow path method to improve calculation of flooding risk in low-lying and newly developing areas.

Keywords: GIS, Arc Hydro Tools, LiDAR, DEM, Overland Flow Path.

1. INTRODUCTION

Although regional authorities in Australia provide information on major riverine flood and tidal flood risk to local land use planners, overland flood risk management at the individual parcel or property level is the responsibility of local governments. Local practitioners need access to detailed overland flow paths in order to manage local flood risk. Such datasets can be prepared using comprehensive hydrodynamic models or visual interpretation of topography contours. The first approach is generally beyond local governments' budget, experience and scope of work, while the simple visual interpretation approach produces site-specific results which might not be valid for flood risk management. GIS-embedded hydrological software such as Arc Hydro Tools offers a compromise, connecting the advantages of modelling water movement with a site-specific view of catchment-scale activity. However, such tools were initially developed for rural areas, while local governments' tasks mostly refer to already developed areas or new estate developments. Thus, Geographical Information System (GIS)-embedded hydrological model such as Arc Hydro Tools need to be customised for use in urban catchment practice.

In this article we review methods of digital terrain model analysis relevant to overland flow path determination, describe our own methods of data integration in the GIS environment to determine an overland flow path in an urban catchment, and detail the results of their application to a township in Victoria, Australia.

2. FROM DEM TO AN OVERLAND FLOW PATH

A GIS-embedded hydrological model, also known as a spatially-based distributed hydrological model, can facilitate runoff management in both rural and urban catchments through enabling determination of the hydrological drainage network. Hydrological drainage networks are a central element in a spatially-based distributed hydrological model that link the hydrologist's knowledge to the real hydrological processes in a given area [1].

Arc Hydro Tools [2] contains a spatially-based distributed hydrological model that is widely used in rural catchment management in Australia. In spatially-based distributed analysis, each pixel has its own elevation, flow direction and flow accumulation values based on water flow from an upslope to a down slope. The procedure includes Digital Elevation Model (DEM) preparation, flow direction determination, a flow accumulation calculation, and finally drainage pattern extraction. Although the standard procedure in Arc Hydro Tools can delineate the drainage network, also known as the overland flow path, it cannot account for the complexity of water movement in an urban setting.

Overland flow path extraction from the raster DEM generally includes DEM preparation in terms of spurious sink and flat area removal, flow direction assignment for every land unit, and a flow accumulation (routine) calculation of the number of upslope cells draining to a given cell. Stream definition and stream segmentation are two major tasks within the process of converting a raster dataset into a hydrological drainage network in a vector data model [2].

2.1 Spurious Sinks and Flat Area Removal

sink and flat area removal is the initial step in a hydrological application of a high-resolution DEM. Spurious sinks (pits) include depression cells and flat areas that prevent water flowing to downslope neighbouring cells in the DEM [6, 8]. They result from errors in the interpolation techniques used to produce the DEM, DEM reconditioning by existing linear water flow collectors like watercourses, or limited DEM resolution [3-7]. A DEM with spurious sinks cannot be used to extract hydrological parameters like a natural overland flow path [9]. Although, based on Tarborton's [10] study, up to 4.7 percent of DEM cells could be spurious sinks, water flows downstream in a real landscape, even if in a subdued relief like a coastal plain area.

Developing a depression-less DEM requires application of a simple smoothing filter technique followed by more advanced techniques [11]. Mark [12] proposed a low-pass filter to remove spurious sinks, but this has some drawbacks, particularly in a subdued landscape; for example, loss of information occurs in the DEM smoothing technique [13, 14]. Also, if a flat area comprises a large portion of the DEM, a smoothing technique is not the appropriate technique for its removal [15]. Some researchers have proceeded by assuming that flat (subdued) areas in the DEM are real features in the landscape, but other researchers have insisted to treat flat areas before assumed using the DEM in a hydrological application [16]. In either case, a full evaluation is required [17].

Commonly-used sink (pit) removing algorithms are the fill sink algorithm, the deepen drainage technique (carving method) and hybrid algorithms. These methods are described in turn below.
The fill sink algorithm [18], following the outlet breaching algorithm [7], the most widely used function in GIS software. Fill sink algorithms have been suggested by Planchon and Darboux [19] and Wang and Liu [11]. Planchon and Darboux's algorithm [19] uses the concept of the depression storage capacity of soil in a hydrological application. Wang and Liu's [11] filling technique increases the elevation in sink cells based on the spill elevation at the outlet of a depression and is not based on the closest outlet to the sink cell. Planchon and Darboux's

method [19], cannot resolve the flat area problem, while Wand and Liu's method [11] uses the shortest path concept to route an overland flow path to the outlet across a flat area.

The carving method is a lowering algorithm [14]. Unlike the filling method, lowering the cells in order to let water flow continuously towards the outlet does not create the flat area problem. This method is useful for subdued landscapes where the extracted channel deviates from known networks.

Hybrid algorithms use the advantages of fill sink algorithms and the carving algorithm. It can also minimize the changes in original DEM to produce the pit-less DEM [20].

Each sink removal method has its advantages and shortcomings in terms of processing time [11]. In addition, while they are appropriate for a 1D hydrological model, these methods do not remove spurious sinks and flat areas appropriately for 2D hydrological modelling [11]. The filling sinks method (raising the elevation in sink cells and then breaching sink routes from outlet methods) creates new flat areas where there are significant problems in delineating the water's overland flow path. Some methods are like the method that has been suggested by [19] and [11] do not deal with flat area problem. Therefore, additional techniques for removing a flat area are needed to produce a hydrologic-DEM. The hydrologic-DEM is a pit-less DEM usable in hydrological applications.

Several methods have been proposed to solve the problem of assigning flow direction in a flat area. Soille and Vogt [14] claimed that the best method to assign a flow network in a flat region is Garbrecht and Martz's [21] method based on a geodesic mask and distance. However, the flat area problem can also be solved by user interference to determine the slope threshold between two cells. The user-determined threshold causes an increment to the relief to achieve the assigned minimum slope between two adjacent cells in flat areas toward the given outlet.

2.2 Fill Sink Methods

In the fill sink method [18], spurious sinks can be filled based on the minimum elevation of the neighbouring cell. However, this technique produces more flat areas which are an important issue in DEM, particularly in a low-lying flat landscape. In addition, treating a complex pit problem is not straightforward [11].FIGURE 1 shows a schematic depression cell before and after filling.

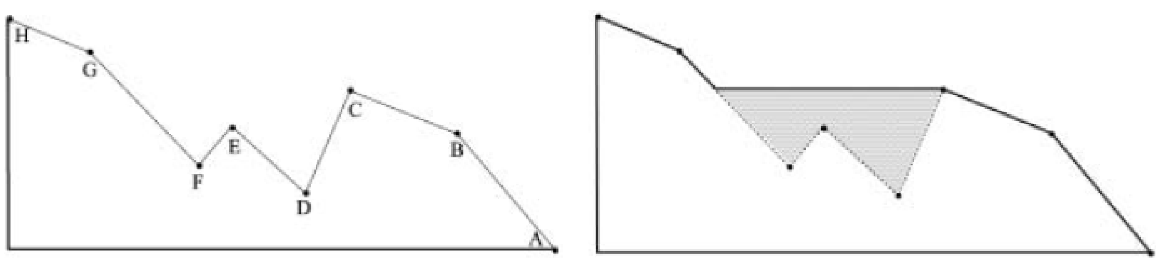

FIGURE 1: Filling algorithm removes the depression but creates a flat area problem (Wang and Liu, 2006).

In FIGURE 1, the left figure shows a spurious sink (pit or depression) problem before filling, the right figure shows the condition after filling using Jenson and Domingue's algorithm [18]. Dealing with a complex depression (FIGURE 1, left) is not straightforward for a filling algorithm and is a time-consuming procedure. In contrast, dealing with sink cells using the shortest path and spill elevation concept, as suggested by Wang and Liu [11], is a straightforward and time-efficient procedure.

2.2.1 The Spill Elevation and Shortest Path Method

The correction of a complex sink area is not easy with the filling sink method due to required frequent filling stage. Therefore, Wang and Liu [11] suggested a spill elevation concept to deal with multiple sink cells at the same time, and the shortest path concept to solve the flat area problem created after filling sinks. FIGURE 2 describes the concept suggested by Wang and Liu [11].

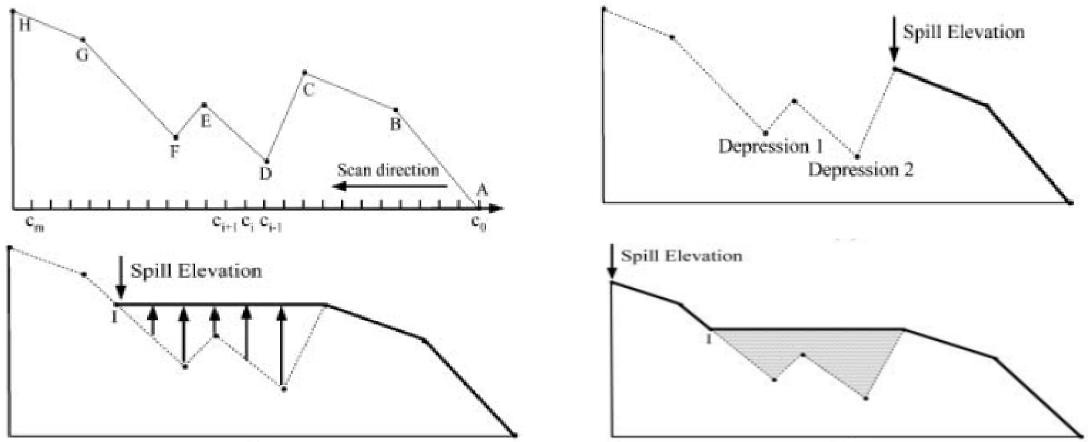

FIGURE 2: Filling sinks through the spill elevation concept in Wang and Liu's (2006) method.

In FIGURE 2, the top left figure shows the sink location (F, D), the top right figure shows the spill elevation determination, the bottom left figure shows the filling of multiple sinks using spill elevation, and the bottom right figure shows the final correction of cell values.

In the shortest path direction from the outlet on the DEM edge, progressive propagation of the spill elevation toward the interior cell can be the threshold for filling the sink cells. Wang and Liu's (2006) method improves upon the conventional algorithms in terms of time and deals with a complex depression faster than Jenson and Domingue's method [18]. A detailed description of different sink removal techniques is presented in Wang and Liu [11].

2.2.2 Carving Method

Unlike sink filling methods, the carving method developed by Soille and Vogt [14] does not create more flat areas. The method uses flooding simulation procedures in order to remove spurious sinks. The same idea can be used in imposing known drainage on the DEM. The method improves the continuity of a delineated channel network. Further advantages of the carving method over the filling methods is that the resultant delineated channel does not include a parallel flow path and the final result does not need to be considered in terms of the flow direction [14]. However, Soille [20] suggested a combination of the two sink removal approaches in order to optimise the associated change in the original values of the DEM. Sink removal algorithms have to be followed by resolving the flow direction assignment over the flat area before taking further steps to establish an automatic extraction drainage network from the DEM.

2.3 Flat Area

An artificial flat area can be created by any errors in the raw surface topography dataset, interpolation techniques or after filling sinks [22]. The flat area in a raster DEM can be determined based on positive downward elevation gradients. In the case of zero (flat) and negative (sink or pit or depression) gradients, the target cell cannot be included in further computations and must be treated as a flat or sink area [23]. Flat area treatment can be done through two types of methods.

The first group of methods includes the shortest flow path technique over a flat area towards the outlet [18], the least cost search algorithm in a flat area [11], and the neighbour-grouping scan technique [24] to assign flow direction over flat areas.

The second type of flat area treatment methods alter the original elevation value in the DEM in order to resolve the flat and sink cells problems. These methods incorporate interpolation and optimisation techniques to deal with flat and sink cells in a raster DEM. Examples of this type of method are Hutchinson's iterative finite difference interpolation algorithms [25]; Martz and Garbrecht's Topographic Parameterisation (TOPAZ) method [16], and recent methods like those of Pan and Stieglitz [23].

2.4 Flow Direction Assignment

Flow direction is a specific term in the hydrological interpretation of the DEM and is defined in order to show the water flow route in each raster DEM cell. Every cell in a raster DEM is limited by the surrounding adjacent cells in eight directions (including the cardinal and diagonal).Water flows over the steepest direction which can be calculated based on elevation differences and the distance between a given cell and its neighbours.

The classical approach for a flow direction assignment on a raster DEM involves the D8 method [3], in which each cell centre is linked to the neighbouring cell centre along a decending flow pathway. The D8 method (FIGURE 3) resolved the hydrological network discontinuity which resulted from Peucker and Douglas's (1975) geomorphological method (which was based on a simple elevation comparison and curvature coefficient [26].

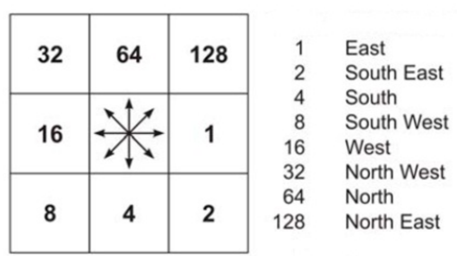

FIGURE 3: Schematic Classical D8 Method (Hutchinson et al., 2008).

However, determining an overland flow path based on no more than eight directions in certain angle is a limitation of the D8 method, as is the assumption that each cell has to show a flow direction. Nevertheless, the D8 method is capable of taking into account a flow with convergent characteristics [26]. Jenson and Dominque [18] produced the first automatic delineated catchment in ARC/Info. Since then, the D8 algorithm has become the most widely used method in different GIS software, despite all the previously mentioned limitations.

Although the D8 method is implemented in various GIS software packages, because of its limitations, other methods have been developed to enhance the flow direction outcomes regarding the reality of water flows in landscapes. the various flow routing methods can be classified into two main groups, as Cimmery [27] suggested: cell-wise linear (single and multi-flow) flow routines, and flow tracing. The second group lets water move around the DEM freely, while the cell-wise group limits flow movement linearly. A linear flow routine can also be classified into single-flow and multi-flow (convergent flow) distribution. The application of methods depends on the terrain circumstances for a hydrological model. Due to the limitations of the D8 algorithm, [5] the random eight nodes (Rho8) was proposed [5]. The Rho8algorithm solved the problem of direction limitation to every 45 degrees (lateral and diagonal), as well as producing a parallel flow by applying a stochastic flow routine algorithm which lets flow move freely on the DEM [27]. A proportioning of a flow between lower neighbours has also been proposed using 1.1 as an appropriate exponent of slope [26]. However, the proposed Rho8 has a problem in creating an unrealistic convergent or divergent flow, while reality shows a parallel overland flow path [28].

In order to overcome the lack of divergent flow in the D8 method, Freeman [29] suggested a multiple flow direction (MFD8) method based on the classical D8 algorithm concept but breaking the flow into different fractions based on the slope-weight between given cells and lower neighbours (FIGURE 4).

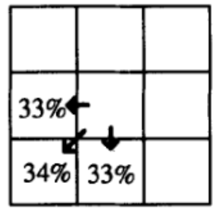

FIGURE 4: Schematic MFD8[30].

The problems associated with the MFD8 model are to [28, 31]:

- define the exponent value, which has been determined 1 [32] and 1.1[29] through various circumstances in the research conducted.
- use a similar algorithm with different landscapes to determine water movement into three down slope neighbouring cells
- create an unrealistic representation of a convergent drainage flow like for a terrain with a well-formed channel
- create fuzzy catchment boundaries leads to an unclear and unrealistically large catchment
- ignore the trend of surface topography

The form-based algorithm [33] was introduced to resolve problems in the linear D8 methods [31] by including the surface topographical trend in the grid DEM analysis. In the new method, the trend of the surface topography is included to extract the flow direction and drainage network. A single-flow algorithm is appropriate for a concave terrain, while multiple-flow algorithms are suitable for flat and convex terrains [28]; a combination of the two types is preferred to model a natural overland flow path [28].

Using the concept of flow tracing to produce flow tube (band) instead of producing linear overland flow path , methods such as kinematic routing algorithm (KRA) [34] and its extended version, the Digital Elevation Model Network (DEMON) [35] were developed. KRA [34] produces a uni-dimensional aspect flow routing and DEMON [35] produces a flow routing based on a bi-dimensional aspect-driven flow movement; the latter is a complex and time-consuming process. Aspect-gradient-based algorithms are more sensitive to DEM errors than flow routing (cell-wise) algorithms which are based on a slope-gradient linear flow distribution like MFD8. In addition, unlike the other routing algorithms, DEMON does not allow for directional movement from upslope cells to a down slope neighbour, so creates a discontinuous surface [28]. Furthermore, the DEMON method yields a significant error on concave and convex terrain landscapes [28]. The Mass Flux Model [36], is a recently developed flow algorithm that estimates flow accumulation based on a free water movement across a surface. Those methods introduced so far are based on the raster DEM, while alternative approaches are based on the Triangular Irregular Network (TIN). TIN is derived using raw sample points or extracted from the raster DEM.

Tarborton [37] designed the D-infinity algorithm to determine the steepest angle among eight facets centred at a grid for finding flow direction; it solves the problem associated with the D8 flow direction algorithms. The D-infinity method represents a bi-flow direction based on triangular facets (FIGURE 5).

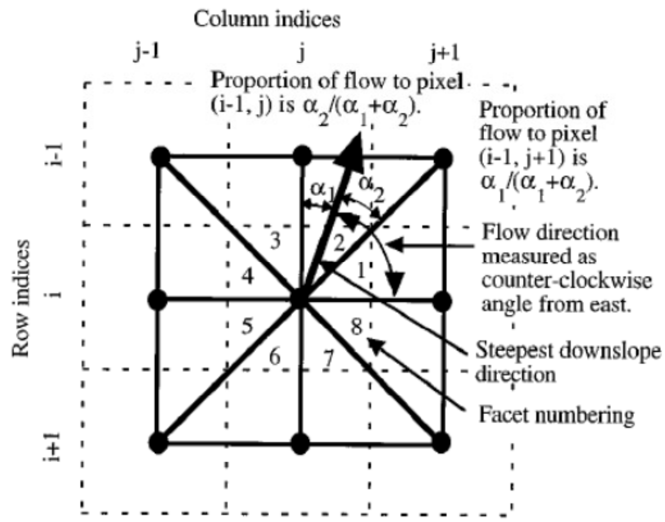

FIGURE 5: A Schematic of the D-Infinity Method [37].

Tarboton [37] noted that raster-based flow direction assignment algorithms are robust, simple, and efficient in terms of storage due to the raster data model structure. Such methods minimise the flow dispersions, but they represent flow direction too coarsely and are affected by bias due to their orientation and numerical grid.

In order to use TIN-based flow extraction Seibert and McGlynn [38] developed the multi triangular flow direction method (MTFD). The method represents the multi-flow direction based on triangular facets. However, the developed TIN is based on the usual approach in which the edges of the TIN direction might not be aligned with the local ridge and valley line and in some places the TIN edge intersects with valley lines [28]. Taking into account the need to match a TIN edge with the local valley and ridge line, Pilesjö [28] introduced a method to form a TIN based on the raster DEM in regards to the local relief. In order to include the landscape trend in a TIN-based model, the form-based algorithm [33] was integrated with the TIN-based algorithm suggested by Pilesjö and Hasan [39]. In all three abovementioned TIN methods, each cell in the raster DEM will form triangular facets.

TIN is more flexible than the raster model and represents a relatively accurate terrain model in the presence of dense LiDAR ground points. However, editing TIN in order to implement an urban feature and extract an overland flow path in a gently sloped area is a burdensome process. Furthermore, major flow path determination can be based on an aspect of gradient analysis using TIN, which is more sensitive than the slope gradient analysis in the raster model in relation to the inherent error in surface topography data.

There are several reasons why TIN might not be chosen for overland flow path determination and watershed delineation. It requires more time and computer power than DEM in raster data structure in order to extract hydrological features. it is also not commonly incorporated in typical GIS environment for hydrological analysis (like Arc Hydro Tools in ArcGIS).

2.5 Overland Flow Path Network Extraction

Although flow direction represents water movement in each cell in a raster DEM, it is not possible to delineate overland flow path unless using flow accumulation (FIGURE 6). Several studies have been conducted to map overland flow path based on flow accumulation model. The most important parameter to map overland flow path is to determine suitable threshold for determining channel head for automatic drainage network extraction [40]. However, the critical threshold value to separate DEM cells into stream and non-stream cells in current GIS-embedded hydrological tools is user-defined. One per cent of the maximum value in a flow accumulation model is the suggested value [2].

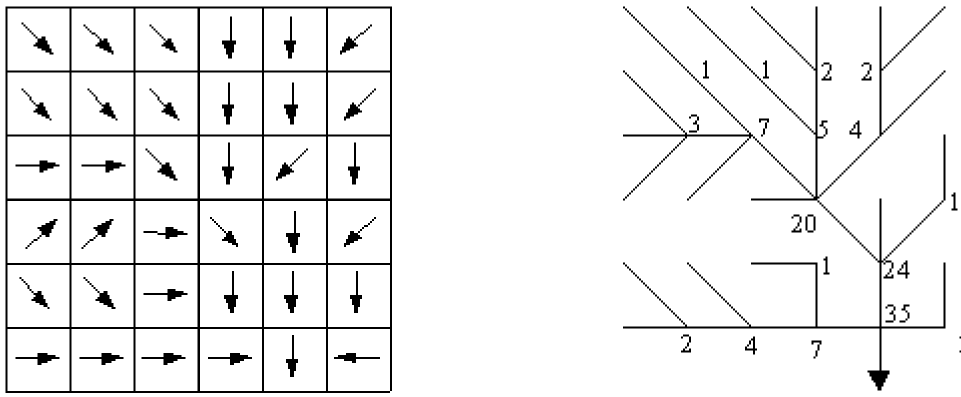

FIGURE 6: Symbolic representation of flow direction (left) and delineated overland flow path (right) from a flow accumulation model [41].

FIGURE 6 shows the flow direction model (left) in understanding a drainage network using its interpretation in the flow network model (right)

A drainage network pattern can be delineated by the flow accumulation, which is dependent on the user-defined threshold, in order to take the upstream catchment area into account. Therefore, sometimes a flow accumulation is known as the catchment area. Separation of DEM cells into stream cells and non-stream cells is a controversial issue in spatial hydrology, and different approaches have been evolved to determine the required threshold in order to initiate a stream channel. Physiographical parameters like climate and soil type influence the threshold [10]. However, the existing GIS-embedded hydrological models use only flow accumulation, which is extracted from DEM. As noted earlier, it has been agreed that 1% of flow accumulation is required to form a channel [2]. The 1% noted in Maidment [2] was determined for rural catchments, and it may not applied in urban catchments due to major and minor system effects which divert natural overland flow into a determined path.

3. STUDY AREA

The case study for this paper was the Inverloch township and surrounding rural areas of the Bass Coast Shire. The Bass Coast Shire Council controls land development and manages the associated water resources. The Bass Coast Flood Management Plan and Stormwater Management Plan (now referred to as the integrated water resource management plan) are two important policy documents. The Bass Coast Shire Council follows these plans in undertaking water resource management related to land development.

Inverloch is a township close to the coast which covers an area of approximately 9km^2 in southern Victoria, around 150km from Melbourne. All drainage water from the area flows into Bass Strait (FIGURE 9).

FIGURE 7: Location of the study area in Australia (http://maps.google.com.au/maps?hl=en&tab=wl, Captured on 8th Oct. 2011).

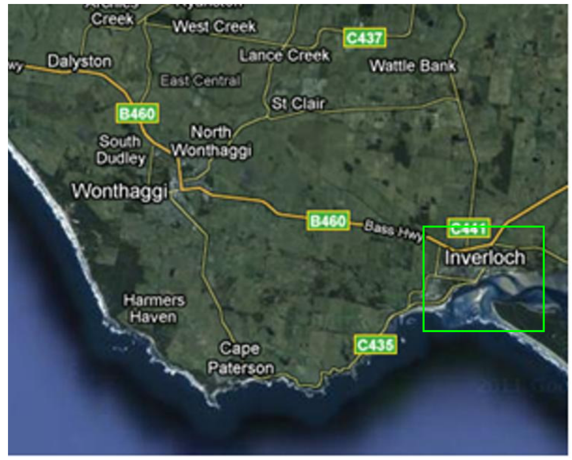

FIGURE 8: Location of Inverloch (http://maps.google.com.au/maps?hl=en&tab=wl, Captured on 8th Oct. 2011).

FIGURE 9: Inverloch township area (http://maps.google.com.au/maps?hl=en&tab=wl), Captured on 8th Oct. 2011).

4. METHODOLOGY

Adapting a rural area terrain analysis to an urban landscape in order to derive hydrological features, an overland flow path and catchment area needs additional spatial details and processing time. Details that must be included are major and minor drainage system structures which divert or collect runoff across a given area away from its natural pathway (
FIGURE 10).

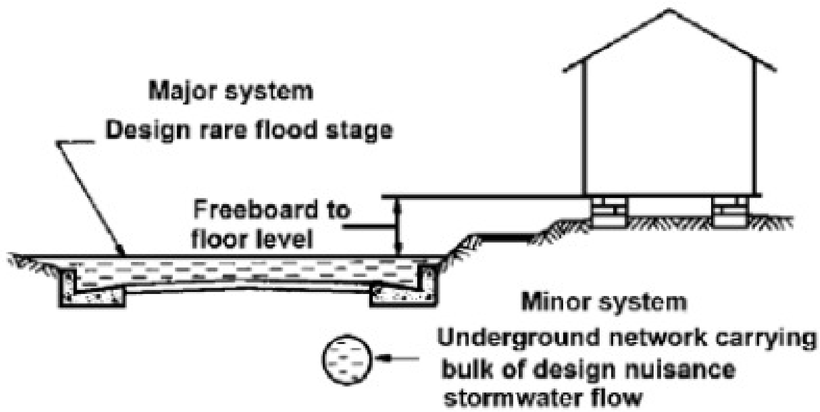

FIGURE 10: Major and Minor Drainage System in an Urban Landscape[42].

A fully automated urban terrain analysis for the purpose of a hydrological model cannot followed based on the process done for a rural catchment [43] and is often impractical due to a lack of required details in spatial datasets and proper spatial data integration. Djokic and Maidment [43] however, have noted that the appropriate approach can be determined based on available data, hardware and software.

LiDAR sample points (available as part of a research collaboration with the Bass Coast Shire Council) were used to develop a 1m resolution DEM for the Inverloch urban and fringe area using inverse distance weight (IDW). A pre-processing step was applied to remove spurious sink and flat areas. Sink removal was performed using the carving algorithm, which is suitable for the study area's predominantly flat coastal urban landscape. FIGURE 11 shows the process for developing a hydrologically sound DEM. The primary DEM was derived using LiDAR sample ground points in 1m by 1m pixel size.

LiDAR bare ground points were converted into the DEM using the interpolation technique, geostatistic IDW; the resultant DEM was then inspected using the hillshade model [1]. Any errors were detected using the hillshade model, so the source LiDAR data was inspected and the incorrect sample points removed. The DEM was converted to a hydrological DEM (Hydro-DEM) through the pre-processing stage.

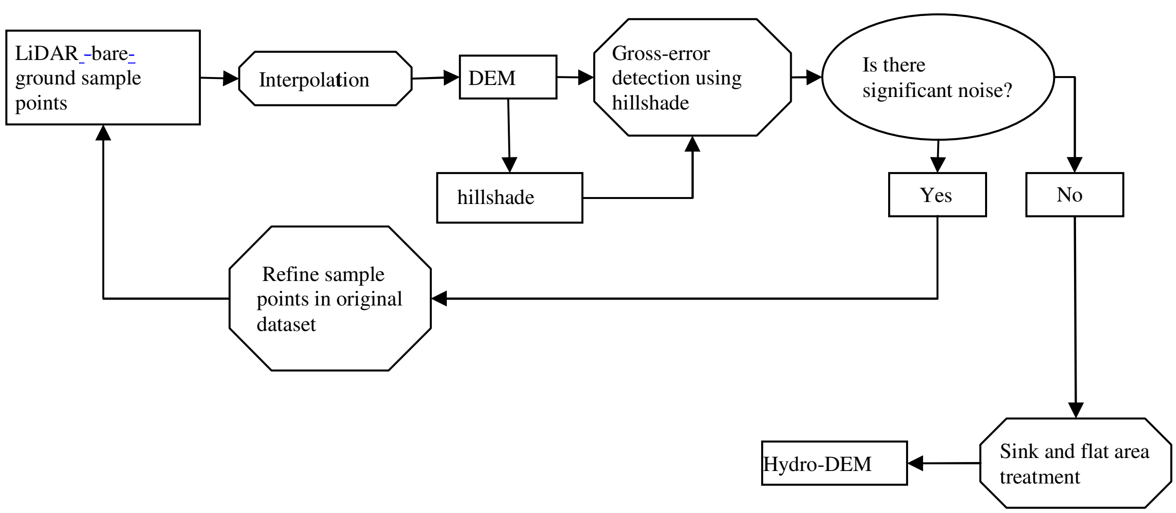

FIGURE 11: General Process Applied for the Extraction of a Hydrologically Sound DEM.

Water movement in urban catchments includes three types of flow: diffused overland flow (sheet flow to the nearest constructed drainage inlet and gap flow in the location of each inlet), concentrated overland flow, and concentrated flow in a man-made network system like stormwater collection pipes. Therefore, one terrain model inadequately represents urban catchment hydrological behaviour [43]. If the analysis includes all types of water movement, then the resultant overland flow path can be called a coupled surface and subsurface flow path, or a gap flow [42]. A gap flow includes the flow which cannot be captured by the stormwater collection system inlets due to its wrong location, insufficient capacity, barriers like rubbish or sediment, and increased runoff due to land use changes upslope. The influence of a minor drainage system in producing a gap flow also depends on the design average recurrence interval (ARI) for a minor drainage system. (The ARI in the study area is five years.) Heavy rainfall causes more gap flows and consequently a large flood flow on the down slope.

A hydraulic analysis is initially required to estimate the gap flow rate, but the required information to estimate the gap flow is not in Bass Coast Shire Council database. Furthermore, a hydraulic analysis is expensive both in time and cost. Alternatively, instead of using a detailed hydraulic analysis, it is possible to assume that the flow which reaches the inlet does not enter the minor drainage system as a whole and so flows over the surface as a gap flow until it reaches other inlets. In the design stage, the amount of gap flow which flows down slope from the location of each entry pit is assumed to be around 50% of each inlet capacity [42]. The latter can be interpreted as meaning that each cell in the DEM which includes entry inlet pits should contribute to the flow accumulation calculation by 50% of transferability. FIGURE 12 shows the process of flow direction assignment correction and flow accumulation calculation used to delineate the gap flow in the urban catchment being studied.

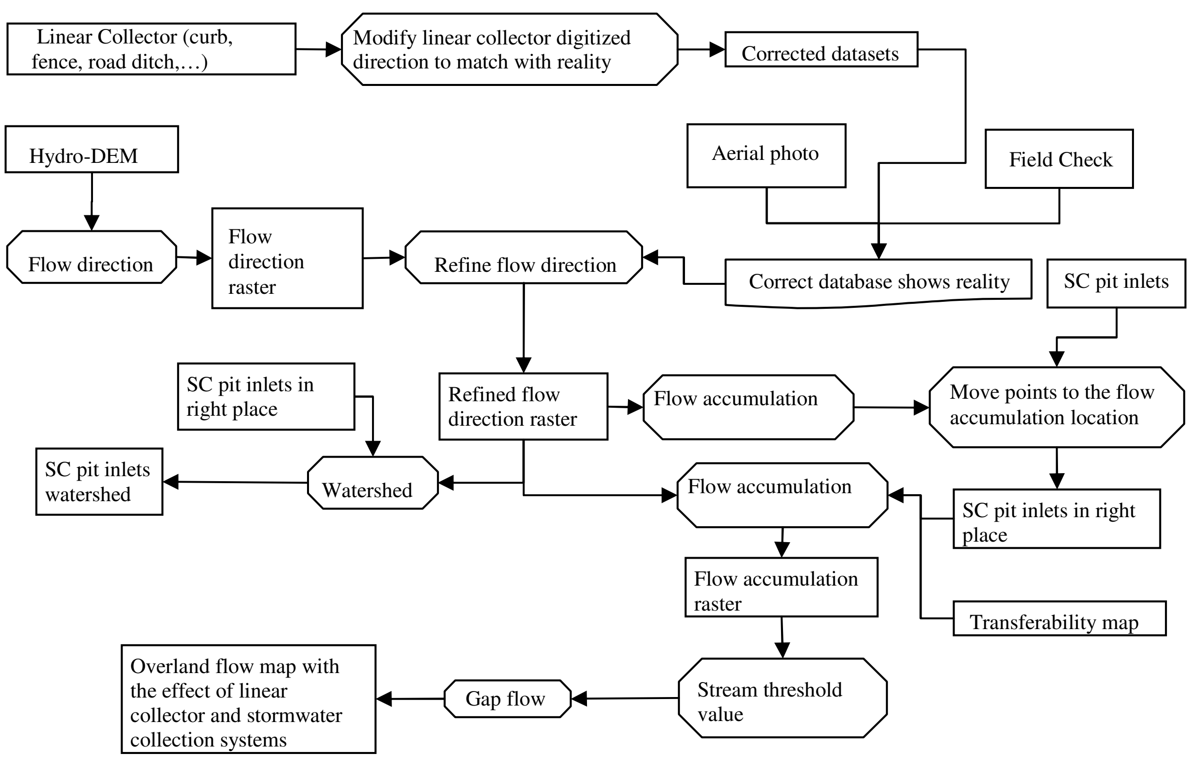

FIGURE 12: General steps for extracting an overland gap flow path in the presence of a linear collector/ in the presence of a stormwater collection system effect.

Although the popular GIS-embedded hydrological models are suitable for rural areas, with some refinements they can also be used for overland water flow path mapping in an urban setting.

5. RESULTS AND DISCUSSION

The results of preparation of the DEM in terms of sink and flat area treatments is presented below, followed by the results of the flow analysis.

5.1 DEM Development and Preparation

The boundary of the study area was limited to areas covered by the LiDAR dataset. The DEM for the study area was developed based on the LiDAR ground sample points using IDW interpolation techniques in the ArcGIS Geostatistical Analyst extension. The developed DEM was pre-processed to remove sink and flat areas using carving method.

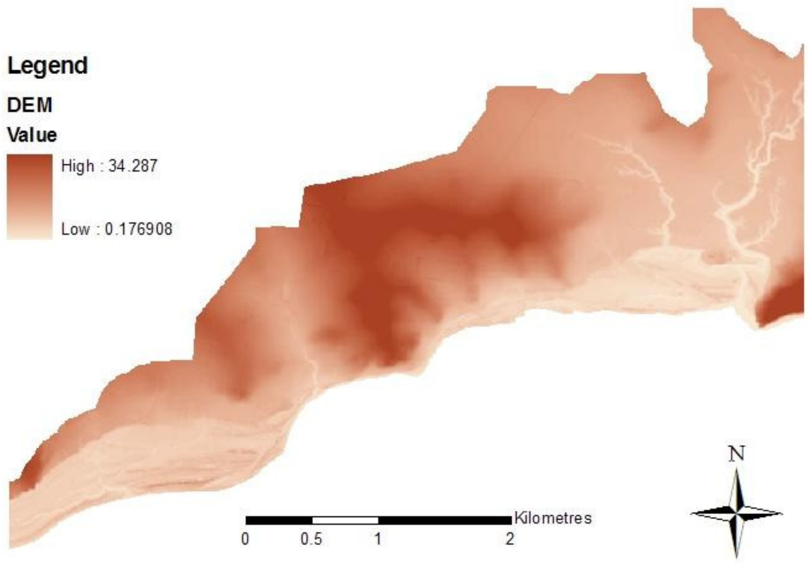

FIGURE 13: Hydrologically sound DEM developed from the LiDAR sample points.

FIGURE 13 shows the Hydro-DEM for the Inverloch township study area. Hydro-DEM has only been treated for sink and depression removal using the hydrological tools in the GIS software. In the next section, we describe how the Hydro-DEM was treated in order to represent the influence of urban features on flow direction and flow accumulation stages.

5.2 Overland Flow (gap flow) Path Determination

Using the classical D8 deterministic flow direction assignment model, the whole Inverloch township study area was analysed for the extraction of the overland flow path. However, the resultant flow path did not acknowledge the complexity of urban catchments due to the rural catchment analysis focus of the GIS-embedded hydrological tools. Complexity in an urban basin results from the presence of stormwater collection systems including curbs, gutters, inlets, and pipe networks, which create a parallel surface and subsurface flow; in addition, man-made linear collectors can change the shape of a natural catchment in an urban setting. Therefore, appropriate spatial data integration is required to include the effect of an urban stormwater collection system in the terrain analysis process. A data flow diagram for assembly of a spatial dataset in order to map the overland flow path in the Inverloch township area was shown in FIGURE 12.

Refinements with respect to flow direction and the flow accumulation model include incorporating the effect of linear man-made collectors like curbs, fence lines and other linear barriers, creeks, and open drains (ditches) aligned with roads as a major drainage system. Culverts and stormwater collection systems including a pipe network and system inlets are typical urban-specific features. Curbs comprise the majority of artificial linear collectors installed to collect overland flow, and drain stormwater into the nearest installed inlet to the subsurface pipe network. Although water flows downstream in a curb and pipe network, curb cross-section properties are different from river or natural channel cross-sections in rural catchments. Therefore, assuming that linear collectors like a pipe network can play a stream role for draining water in an urban context, like Kunapo [44], can introduce undesired errors in overland flow path mapping. For example, an overland flow path entered freely to the pipe network along imposed linear collector on the Hydro-DEM, while the overland flow path interacts with the subsurface flow only in the location of the subsurface network inlets, stormwater collection pits. In addition, reconditioning of the DEM by the stormwater pipe network, like reconditioning the DEM by a natural stream or channel, can cause substantial errors which must be removed in the preparation phase, which is time-consuming and reduces the accuracy of the final product by increasing the number of flat areas due to the removal of spurious sinks. Flat areas are important barriers in overland flow path mapping, particularly in an essentially flat landscape.

We began the process described in FIGURE 12 by modifying the linear collector dataset direction based on surface topography, then used the modified datasets to refine the primary flow direction model. After developing the first flow accumulation model, stormwater collection inlets locations were modified to be located exactly at the place of concentrated flow (as is assumed in stormwater collection system engineering design). Flow accumulation was then recalculated by including the water trap effect of each pit inlet. It was expected that a less concentrated flow after inclusion of pit inlets would be found due to the collection of stormwater by the stormwater collection system. Each pit trap volume was assumed to be based on the pit type (grated pit, side entry pit, and mixed grated-side entry pits), surface elevation at the location of inlets, and surface slopes. The result of the flow accumulation was then classified based on the favoured threshold for delineating the overland flow path in the study area.

FIGURE 14 shows the flow path extracted from the threshold flow accumulation process (the threshold is set for 5000 upslope cells) in part of the study area, before introducing the effect of inlet pits into the flow accumulation calculation. FIGURE 15 shows the same area flow accumulation with the inclusion of pit trap effects. FIGURE 15 shows that the transferability's effects of the sequential pit inlets reduced the value of the flow accumulation.

Our analysis shows that a part of the concentrated flow is not joined with the other parts. This is because the value in the corresponding cell(s) cannot meet the defined threshold value units (chosen arbitrarily 5000). As can be seen in FIGURE 15, four sequential pits (Pit_1, Pit_2, Pit_3, Pit_4) with a 75%, 50%, 25%, and 0% transferability values respectively, were included in the flow accumulation calculation. Including the pit effects reduced the calculated flow accumulation and consequently concentrated overland flow. As noted earlier, the trap value can be assumed as being 50% of the flow accumulation value in the location of inlets in a maximum assumption.

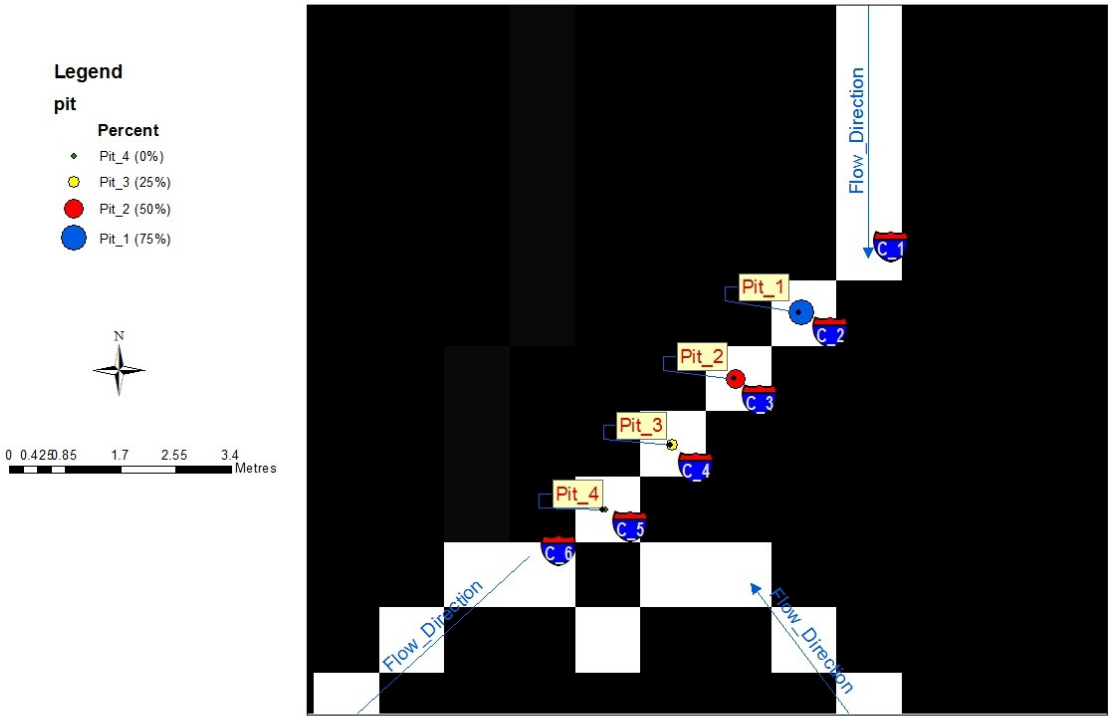

FIGURE 14: Concentrated flow without inlets' trap effect (blue line shows Flow_Direction).

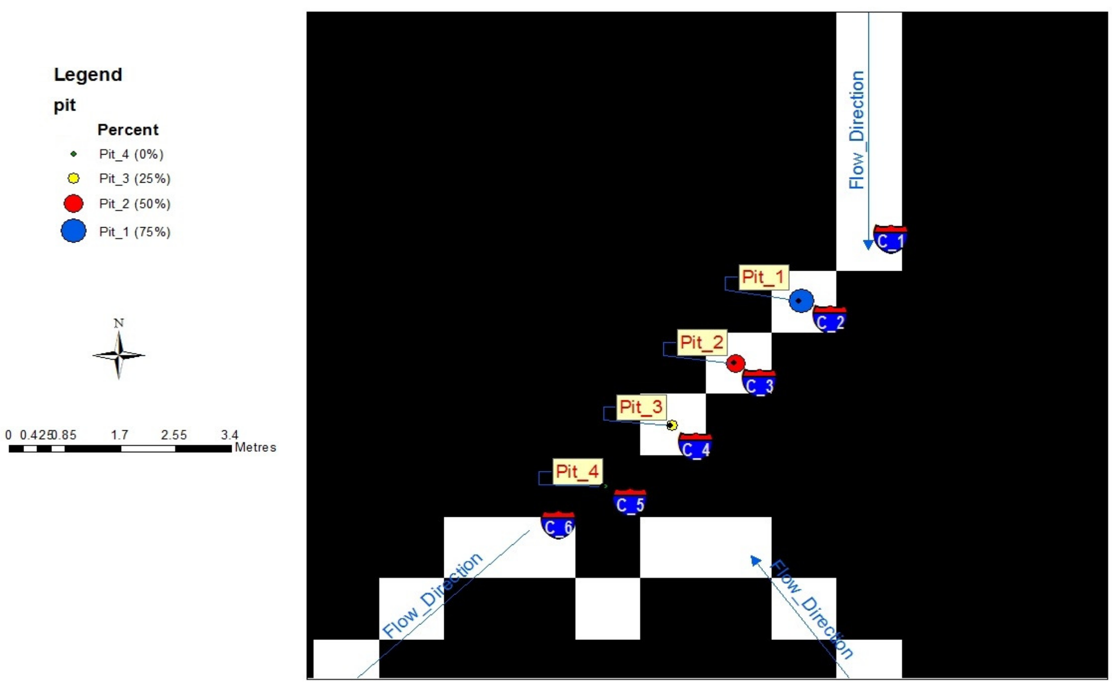

FIGURE 15: Concentrated Flow with Pit Inlets Trapping Effect.

As not every inlet capacity was available for this study, and the aim of this study was based on the conceptual GIS-embedded hydrological model, the inlets' trapping effect was ranked relatively using parameters like inlet types (side-entry, grated, grated-side entry), and the local surface slope at the location of each pit inlet. Using this concept, an overland flow path resulting from the gap flow was delineated for the study area (FIGURE 16).

Pit_1, Pit_2, Pit_3, Pit_4 are located at the cells of C_2 to C_5, respectively. C_1 is the cell drains water to the C_2, location of Pit_1. Flow increasingly accumulates when it follows from C_1 to C_6 if no trap exists. The value of flow accumulation changes in the presence of subsurface network inlets based upon the trap coefficient (1 - transferability) of each inlet. The influence of inlet based upon its trap coefficient in compare with no trap scenario is shown in Table 1.

Cell	Pit	Water accumulated value (no inlet)	Water accumulate value(with inlet)
C_1		28816	28816
C_2	1	28829	28829
C_3	2	28831	28731
C_4	3	28833	10814
C_5	4	28835	2706
C_6		41398	12563

TABLE 1: Comparison Between Trap Existing Scenario and No-trap Scenario.

Table 1 shows that the effects of inlet water trapping effect. The figures in the Table 1 in this study show the unit-less number of water drains to target cell. C_1 receives 28816 unit of water, then water drains to C_2 and accumulated to 28829 with water flow received from the other neighbouring cells. Pit_1 located in C_2 but its effect appears for water units drains to C_3. Water unit decreases to 28731 units while it is 28831 in the model without trapping effect. 28731 units of water flow to C_4 but the effect of Pit_2 decreases it to 10814 in C_4. The effect of Pit_3 decreases the 10814 to 2706 unit, which is less than 5000 unit as determined threshold. Therefore, C_5 cannot be classified as concentred flow.

The unit value in C_6 shows significant difference between 41398 and 12563 before and after inclusion inlets trapping's effect, respectively. It also shows that major overland flow path contributes to C_6 was removed due to presence of stormwater collection inlets.

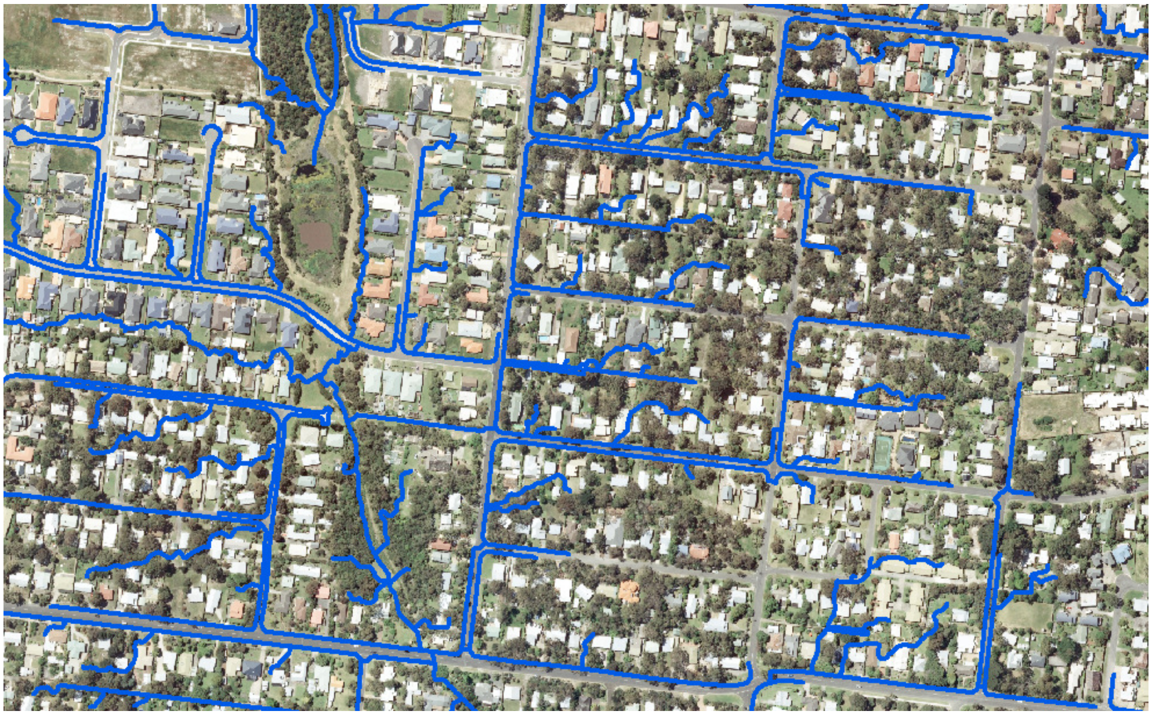

FIGURE 16: The overland flow path in part of the study area after inclusion of pit trap coefficients.

The blue lines show the overland flow path in the study area, Inverloch Township.

6. CONCLUSION

In this article we noted the inability of existing GIS-embedded hydrological models (in our study, we focused on Arc Hydro Tools) to extract an overland flow path in an urban catchment. We described the development and application of an overland flow path extraction procedure that overcomes this limitation by acknowledging the effects of linear collectors such as curbs and the stormwater collection system. We tested our spatial data integration method in a GIS environment using a customised LiDAR-derived DEM for Inverloch, a town in the south-east of Victoria, Australia. The method is robust and - given availability of suitable data and GIS tools – can easily be applied to other urban areas equipped by stormwater collection systems to improve flood-risk-based land use planning and stormwater management.

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