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Advances in Spatial Mapping of Waterways

ABSTRACT

Substantial advances in Geographic Information Software (GIS) capabilities and improved access to detailed digital elevation models (DEM) produced from LiDAR (Light Detection And Ranging) has improved the quality of waterway mapping which also allows for detailed analysis of waterways over large areas. Studies of waterways over large areas are usually determined from large grid size (20-30 m) DEMs. In this work, a detailed waterway network was created over a 1096 km² area using a 10m DEM. Studies of this type over such a large area are rare because of the lack of suitable raw data and the amount of work and cost required to create and process the data. The motivation for this work came from a requirement of the Ipswich City Council (ICC) for an upgraded stream ordered waterway network to support their vision for healthier waterways within the city (Kavanagh, 2009). The new high quality stream ordered waterway network enables the identification and prioritisation of riparian corridor management activities along waterways and facilitates the monitoring and improvement of water quality.

The paper compares waterways from a 20m DEM created in 2004 derived from 5m contours with waterways created from a more accurate and comprehensive 10m DEM created in 2012 from LiDAR data. The study included an assessment of the DEM data and variable parameters such as the most suitable grid scale and catchment input resolution to understand variations in the formation of the waterway networks. Results indicate an approximate 20% increase in lengths of waterways with the new LiDAR based waterways. When compared with the 2004 digital waterways, the additional waterway lengths have the potential impact significantly on cost of remediation of waterways and potentially on the results of water quality modelling. The work illustrated that, in an area such as the ICC, improved waterways created from LiDAR data are suitable for use on a whole of local government authority basis, albeit with a requirement for two stream ordered networks. One network for general waterways locations and lengths, and another more detailed, network for assessment of runoffs and flood studies.

KEYWORDS:

Digital Elevation Models, Waterways, Geographic Information Systems, LiDAR, Ipswich

1 INTRODUCTION

A stream ordered waterway network is a simple classification system for the hierarchy of waterways within a catchment area. The order of a stream network provides a system for classifying waterways based on their number of tributaries (Encom 2012). The Strahler method of stream ordering waterways used in this work is based on the classification system developed by Arthur Strahler in 1957 (Strahler 1957) and is the most common stream ordering method in use (Encom 2012). Waterways which start at a source (i.e. have no flow into them from upstream links) have an order of 1 (Higham 2009). The stream order increases when waterways of the same order intersect. Therefore, the intersection of two first-order waterways will create a second-order waterway, the intersection of two second-order waterways will create a third-order waterway, and so on (ArcGIS 2012). The intersection of two waterways of different orders, however, will not result in an increase in order. The intersection of a first order and second order waterway will not create a third order waterway, but will retain the order of the highest ordered waterway (Encom 2012) as indicated in Figure 1.

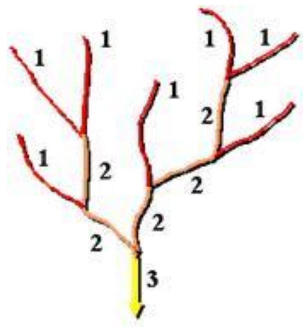

Figure 1: Strahler Stream Ordered Waterways (ArcGIS 2012)

To create accurate stream ordered waterways using GIS a high quality DEM is required. An accurate, high resolution DEM created from 2009 Department of Environment and Resource Management (DERM) LiDARdata was available for almost all of the 1096km² study area. A small area (6.5km²) on the southeast tip of the study area being the only area not to have the high-resolution data. The DERM derived DEM covered 99.4% of the study area

Results from previous studies have shown that better quality data delivers improved waterways. Wang et al. 1998, investigated comparisons between 1:250,000 and 1:24,000 and noted that the estimation of the mean gradient parameters based on the 250K DEMs seems to improve with increasing terrain complexity. Results showed that superior estimations were produced from the 24K DEMs (Wang et al. 1998). (Harris 2008) found that accurate waterways could be derived from DEMs that were created from various raw data sets. However, DEMs derived from information such as 5m contours is less suitable in flat areas, data such as LiDAR being more detailed allowing for the creation of more accurate waterways.

A better understanding of the types and lengths of waterways allows for a better understanding of pollutant loads and therefore possible improvements to water quality through better management practices across the region. Knowledge of waterways lengths and runoffs allows for costing of ways to reduce sediment and nutrient loads to our waterways and bays (Melbourne Water 2008). Estimation of lengths also allows for the judgement of impacts of run-off from proposed changes in use of land through which the waterways run.

1.1 Software Capability Improvements

In the past few years the number of applications that use three dimensional information representing topographical objects has increased rapidly (Elberink et al. 2006). The results section of this paper supply give an indicative understanding of the improvements of the advances in DEM quality (and therefore waterways) created using GIS hydrology software in the period between 2004 and 2012.

Two MapInfo based hydrology software sets were used for the majority of processing in this study. Vertical Mapper/Streambuilder for the 2004 waterways (that are used for comparison purposes in this paper) and Discover was used for the processing of the 2012 waterways. Vertical Mapper processes approximately two million points, which compares unfavourably with the newer Discover, which processes approximately one billion points. Whilst the processing of points to create a DEM surface has improved a great deal during this period, this does not necessarily apply to the generation of waterways within the areas.

Streambuilder, which was used in conjunction with Vertical Mapper, was capable of processing grids produced within the software. However, Discover, which can process grids and associated waterway networks, is not capable of processing the grids for waterway construction that it, itself builds. For instance in the case of this work, Discover was unable to process into waterways a 5 m DEM of the study area that was processed using the same software. Where required, the process to resolve the issue of being unable to process an area involved the splitting of data into smaller components. Large data sets (DEMs) can be split into sub areas (or sub catchments) with data sets (such as waterways) being created within these smaller areas being "stitched" together after processing. Consideration then needs to given to the resulting stream order to ensure that waterways derived from the smaller areas are allocated their correct stream order.

This paper investigates waterways created with the use of a 20m DEM created in 2004 from 5m contours and compares them with waterways derived from a 10m DEM created in 2012 from Lidar data. The 10m DEM also allowed for testing and determination of the most appropriate detail of waterway network over the study area. Lidar derived DEMs were used to create stream order mapping across the Ipswich local government area and allow for the assessment of the most suitable scale of waterways for the Ipswich City Council area.

2 WATERWAY NETWORKS

A waterway network is the interrelated pattern formed by a set of streams in a certain area (Ranalli et al. 1968). The quantitative description of waterway networks was pioneered by Horton, Strahler and Shreve (Tarboton et al. 1991). (Chow et al. 1988) identified that Horton (1945) and Strahler (1964) were the first people to define methods of defining stream order. Strahler slightly modified the Horton technique of designating stream order, to overcome the difficulty of different headwater tributary numbers as necessary in the original Horton scheme (Strahler 1957; Leopold et al. 1964, 1992). Strahler would restrict the designation of order to stream segments (Leopold et al. 1964, 1992). This enabled a more straightforward approach to waterway network analysis, enabling them to be designated with stream order without having to have knowledge of the waterway itself.

3 METHODS

3.1 Purpose of the Study

The Ipswich City Council required refinement of the stream ordered waterway network mapping data for the entire council area. The refinement of waterways was required for multiple purposes, which included:

- Development of a waterway overlay and code for the next Planning Scheme review,
- Waterway mapping and data for catchment and sub-catchment flood studies,
- Planning and costing of waterway rehabilitation projects, and,
- Identifying and defining appropriate riparian corridor buffer widths for various stream ordered waterways

The stream ordered waterway network also needed to be consistent with the existing regional mapping, including the stream order numbering for major waterways.

3.2 Study Area

The study area comprises a total area of 1096km² and ranges in elevation from approximately 5m to 700m, stretching from Marburg in the north to Purga in the south and from Ipswich in the east to Grandchester in the west (approximately 35 kilometres north to south and 55 kilometres east to west) as shown in Figure 2.

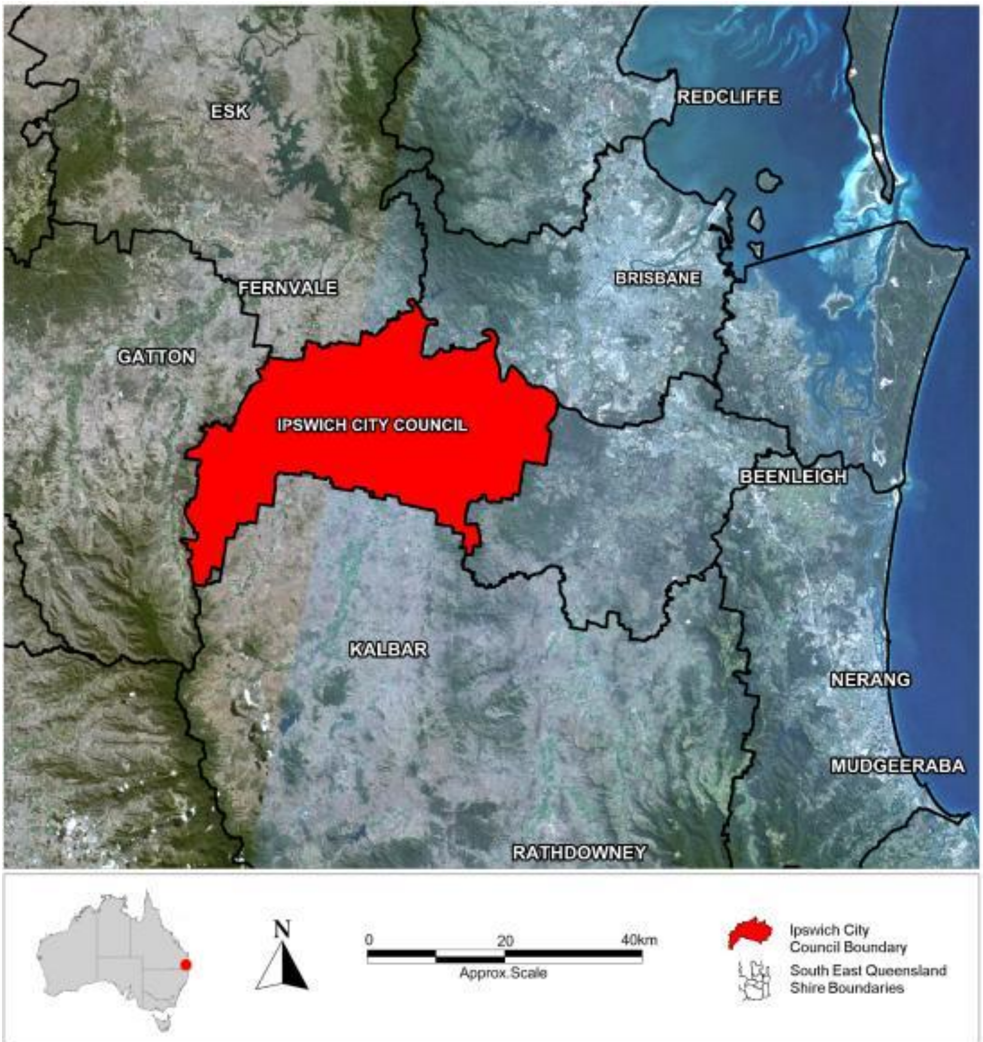

Figure 2: The Study Area

3.3 Data Sources

Data for the development of new waterways was derived from Lidar captured by the Queensland Department of Environment and Resource Management (DERM) in 2009. The DERM LiDAR data has a vertical accuracy within 0.15m (RMS) and horizontal accuracy within 0.45 m. Horizontal coordinates were based upon Map Grid of Australia (MGA) Zone 56 projection and height referenced to Australian Height Datum (DERM 2009). The ICC supplied DEMs based on the DERM LiDAR were at 20, 10 and 5 m resolution. The extent of the DEM coverage is shown in figure 3, whilst figure 4 illustrates the variation in detail between the 2004 20m and 2012 10m DEM.

The 2004 waterways used for comparison in this work were created from a 20m DEM that was developed using data supplied by various federal, state and local government agencies. The 2004 waterways were created for the South East Queensland Healthy Waterways Partnership and the digital elevation model in areas such as Ipswich was predominantly built using 5m contours from 1:25000 topographic maps.

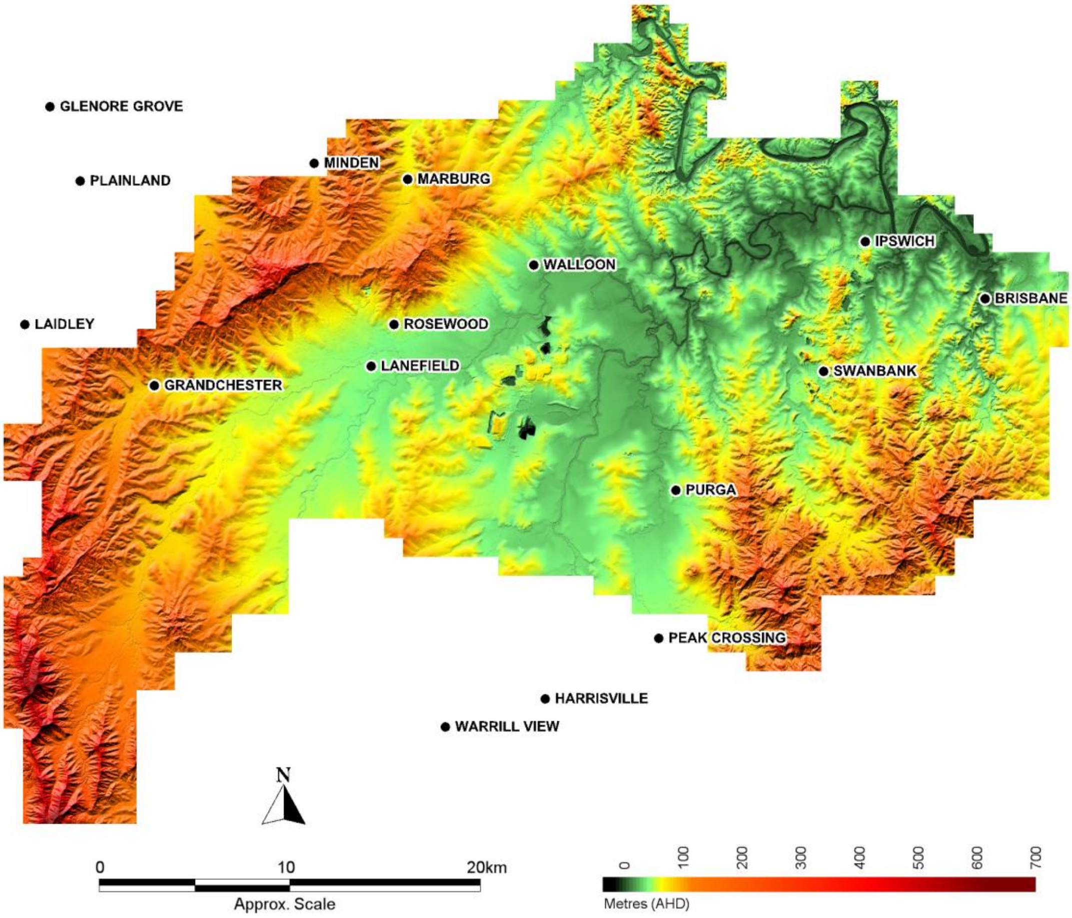

Figure 3: 2012 Ipswich DEM

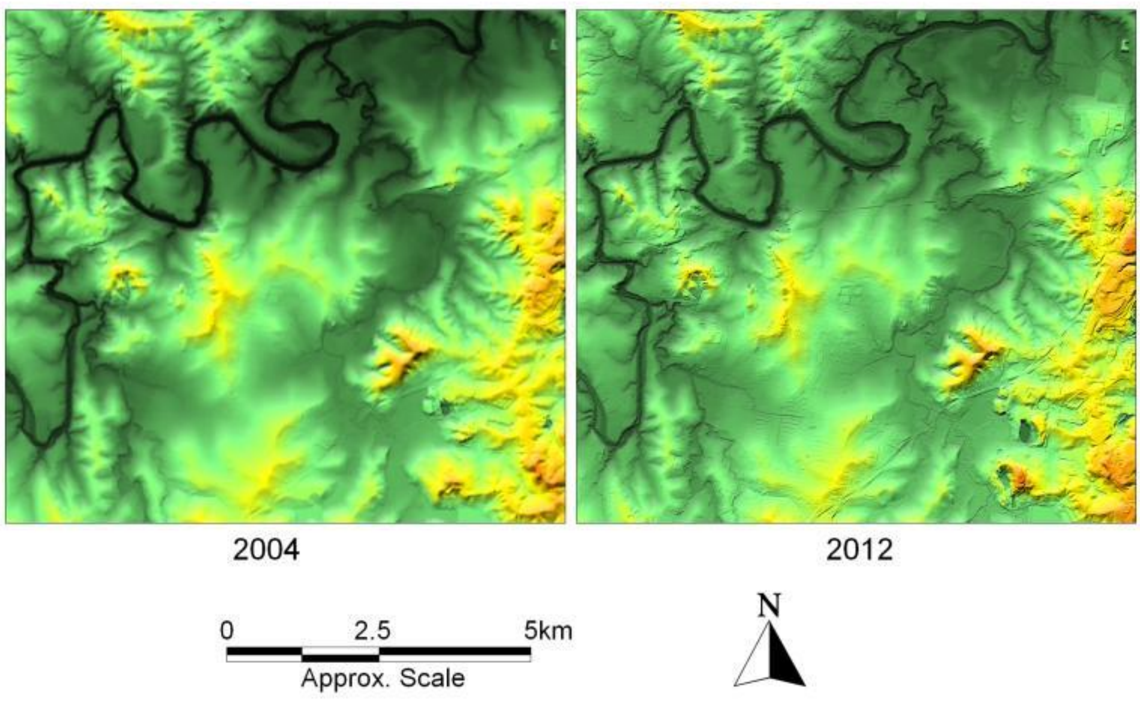

Figure 4: 2004 (20 m) and 2012 (10 m) DEMs

3.4 DEM Development and Scale

The high resolution DEMs for this study were built with Discovery software and the waterway networks were built using a combination of Discovery, Vertical Mapper and Streambuilder. Other software previously trialled during the waterway development process included ArcGIS and TAUDEM. Results from all software provided similar results, but the availability of data for this work in MapInfo format and the necessity to provide results in that same format were the principle reasons for its use. They were built/processed using a common projection system, MGA94, Zone 56. The data development process is described in Figure 5.

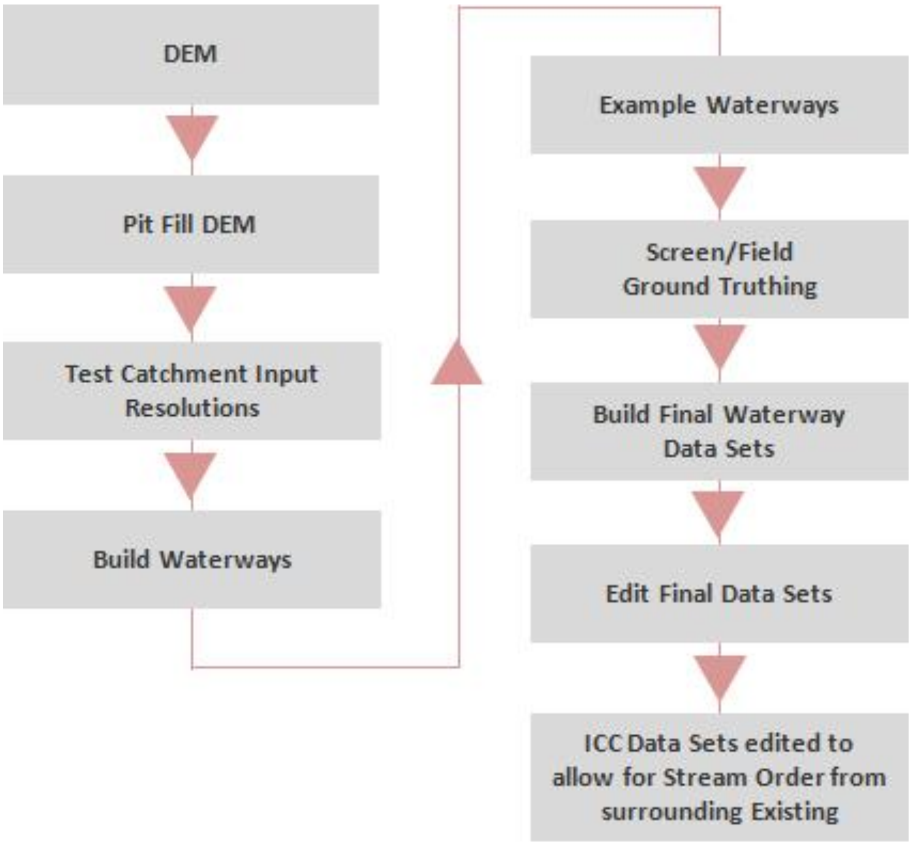

Figure 5: Data Development Process

Initially, 20m 10m and 5m LiDAR derived DEMs were to be utilised to assess the most suitable DEM to use for this work. However, due to memory and processing constraints, the 5m DEM was not processed. As the 10 m DEM processed waterways for the whole study area it was decided, based on the quality of the output not to use the 20 m DEM.

3.5 Pit Filling

Cultural features, such as roads, railroads, and driveways, can make it difficult to generate a stream network from Lidar data by blocking the path of predicted overland flow (Kalakay 2011). These obstacles can be “smoothed away” to some degree, but the amount of smoothing needed to totally overcome the effects of a roadbed, for example, would also eliminate the benefits of having high-resolution LiDAR data to begin with (Kalakay 2011).

Pits may be encountered in DEMs, these hollows will cause a flow hiatus and result in a disconnected drainage network (Higham 2009). All DEM data to be used for waterway network delineation has to have pits filled to enable the flow of water across the surface of the DEM. The more detailed and accurate the data tends to create more barriers to overland flow and therefore tends to create more pits than would be found in a smoother or lower-resolution DEM (Kalakay 2011).

For hydrologic applications, a DEM needs to be pre-processed to ensure that any pits are filled (Higham 2009). Pits are determined by identifying the flow directions in a group of adjacent cells. GIS hydrologic software locates the pits and fills them allowing water to flow across the surface. The pit fill process involves filling up depressions in the topographic grid surface by detecting cells, or groups of cells, that are lower than all surrounding cells. These cells are then raised to the elevation of the lowest surrounding cell (Encom 2012). Regardless of how large the pit is, the GIS software will attempt to fill it so that it drains out towards the edge of the DEM (Higham 2009). Figure 6 illustrates the pit filling process, where a pit is filled to match the lowest surrounding cell allowing for flow across the surface of the DEM.

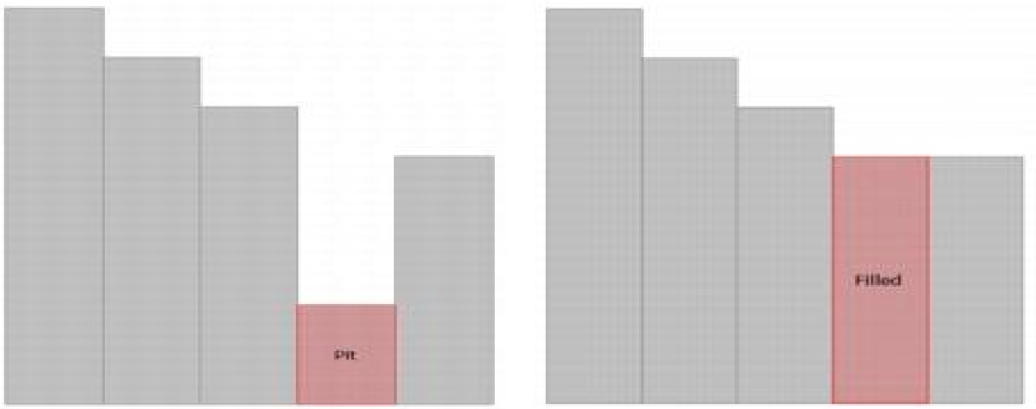

Figure 6: 2D representation of Pit Filling (Encom 2012).

3.6 Minimum Basin Area (Catchment Input Area)

Waterways were delineated from the DEMs using various input catchment areas to test the appropriate input catchment resolution area for accurate waterway creation (Harris et al. 2012). Different input catchment resolutions can be used to determine an accurate starting point of the waterway polylines. The catchment input resolution defines the smallest area that the software will create a waterway network (Harris et al. 2012). The smaller the area, the more detailed the waterways will be (as displayed in Figure 7) (Harris et al. 2012). Catchment input resolution was a critical component of this study defining the commencement of a first order waterway. Small input catchment areas will define more first order streams and increase the network detail and therefore lengths and locations of waterways. A smaller minimum area will result in streams that are more detailed and smaller catchments. However, processing time will be longer. To ensure accurate representation of streams in the ICC area, sample waterways were created at three first order catchment input definitions, namely 0.01 km^2, 0.05 km^2, and 0.025 km^2 as shown in Figure 7. This newly created information was initially checked for accuracy with aerial photography.

Stream ordered waterways (using three catchment input resolutions – 0.1 km^2, 0.05 km^2, and 0.025 km^2) from the 10 m DEM were supplied to the ICC for consideration (See Figure 7). ICC ground truthed the delivered sample data across the shire and decided that the 0.1km^2 and 0.025km^2 data, See Figure 7: The 2012 0.1 km^2 and 0.025 km^2 waterways were considered suitable for use based on different applications required by the ICC. The 2012 0.1km^2 data was then compared with the available 2004 0.1km^2 waterways data. Figure 8 displays the difference in the two data sets.

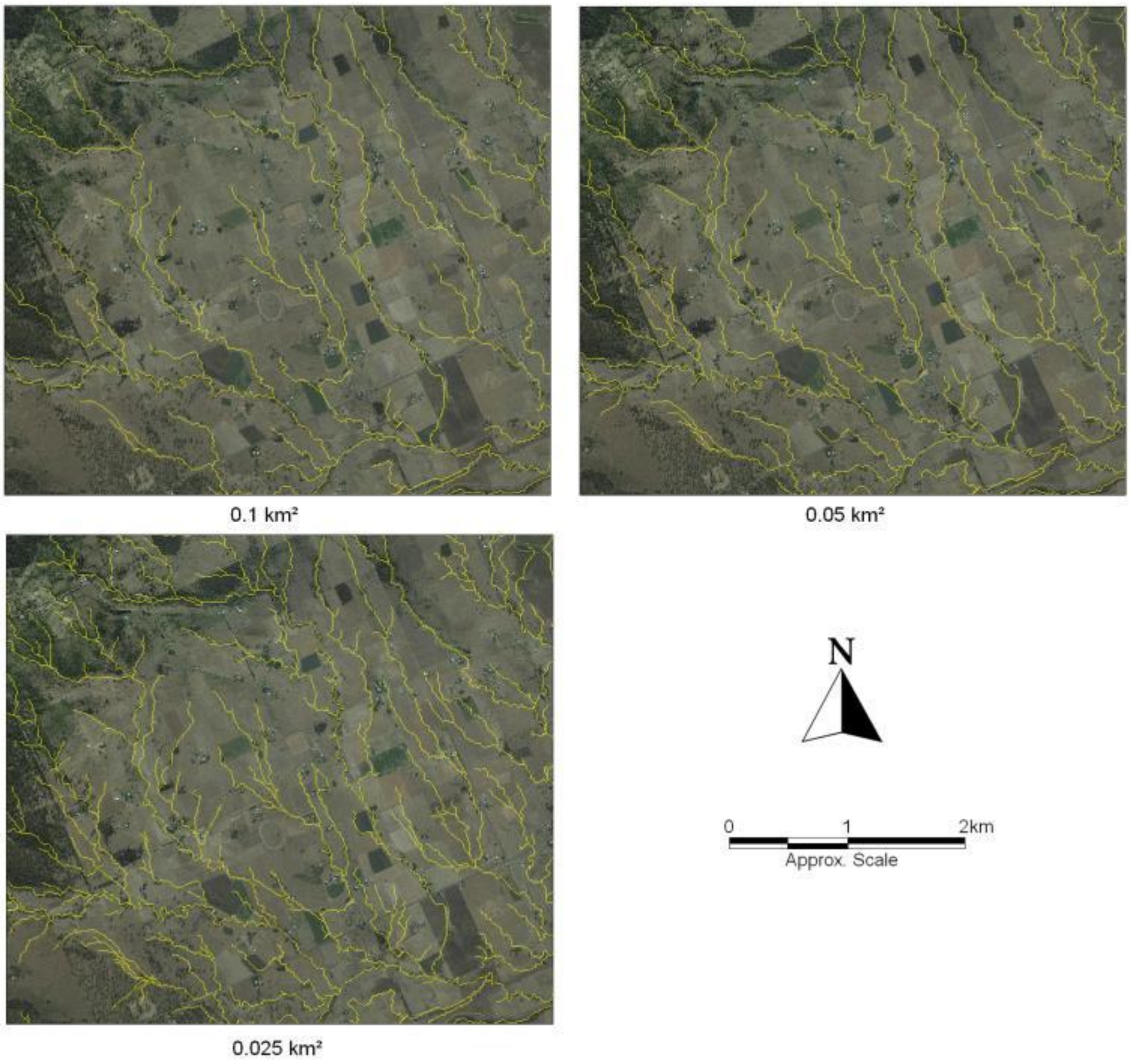

Figure 7: Waterways Derived from 2012 DEM at 0.1 km², 0.05 km² and 0.025 km ² Catchment Input Resolution

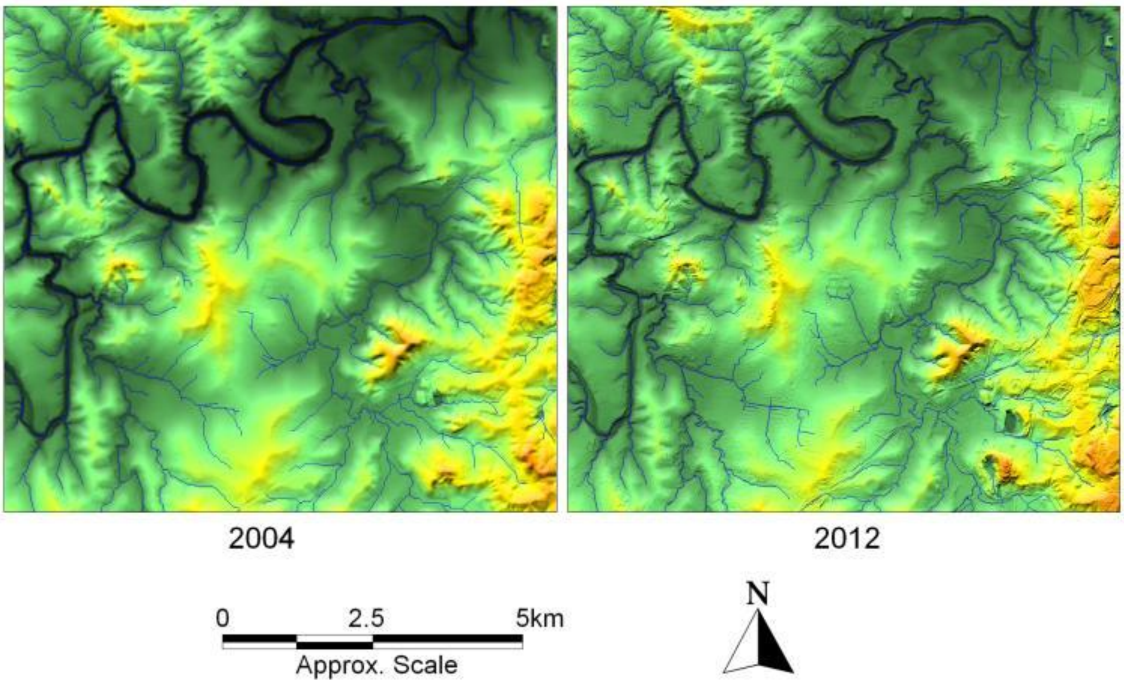

Figure 8: Waterways Derived from 2004 and 2012 DEMs at 0.1 km² Catchment Input Resolution

3.7 Generation of Waterways

Hydraulic information can be extracted for the analysis of waterways from various GIS software (Tarboton 2013). Software can create catchments and drainage networks using the basic principle that water flows from areas of higher elevation to areas of lower elevation (Encom 2012). Using a pit filled DEM, GIS software calculates a related flow directions grid. Using the flow directions grid, a second related grid is calculated where each cell is assigned a value of the number of upslope grid cells that flow into it (Higham 2009). For each outlet, the grid cell containing the outlet is identified and the drainage catchment is then generated by working upslope from the outlet cell using flow direction and upslope area values (Higham 2009).

The grid cells which flow into the outlet cell are assigned to this catchment and the entire drainage area is converted to a boundary and written as a polygon region, together with the table attributes of the outlet point (Higham 2009). With definition of waterways using modern GIS software techniques comes the opportunity to supply more than just the location and stream order of the waterways. Typical attributes that than can easily be created using GIS are displayed in Table 2.

Table 2: Typical Waterway Attributes

Attribute	Description of Attribute
Stream_Order	Stream order in waterways network hierarchy
Length (km)	Length of segment of stream ordered waterway
Unique Stream Identifier	Incremental number of waterway in the area processed
Basin Identifier	Catchment number
Start/End Location	Co-ordinate at the start and end of waterway section
Start/End Elevation	Elevation at the start and end of waterway section

3.8 Re-ordering and Removal of Waterways

3.8.1 Re-ordering Waterway Stream Order Numbers

Stream ordered waterways are usually created within the boundaries of a catchment so that the stream hierarchy can be fully assessed. However, the mapping of the ICC DEM was limited to the extents of the ICC boundary, which caused irregular stream order numbering where the head of the stream is outside of the ICC boundary. Therefore, waterways that flowed into the ICC boundary were used to update the stream order value of the waterways created just within the ICC area (See Figure 9). For this work, the waterway stream order values created for the 2004 waterways were used to update the ICC data. The Brisbane River, Mid Brisbane, Upper Brisbane, Lockyer, Bremer and Logan Albert catchments all impact on stream orders within the ICC area.

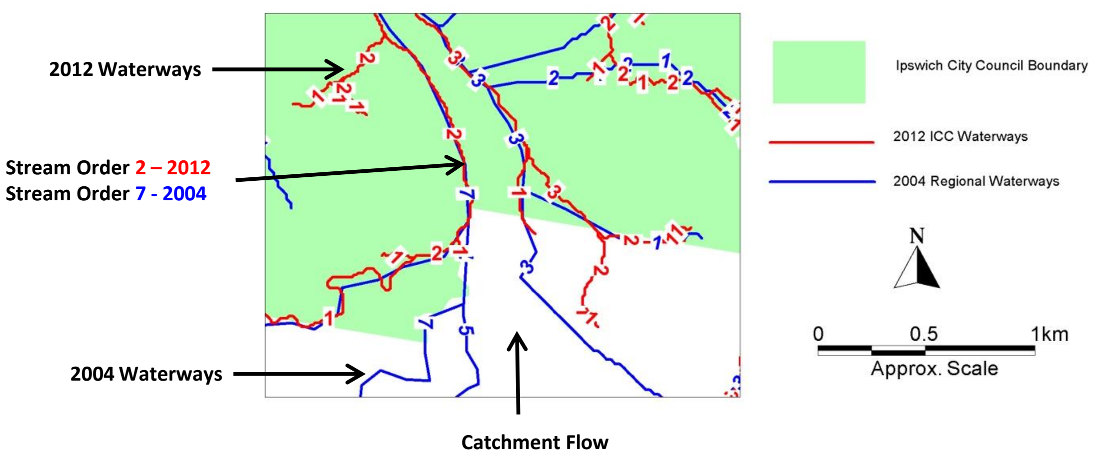

Figure 9: Stream Order Update

3.8.2 Removal of Waterways in Areas of Development

Figure 10 displays waterways created in an area of the ICC that has been developed. The GIS derived waterways are incorrect in areas where piped and open drainage networks act as the main method of drainage. Waterway networks in these areas need to be removed after processing or the areas set to null during the creation of the waterways using the GIS software.

As with the flowing of higher ordered waterway numbers into the shire boundary (3.8.1), waterways that have been cut in urban areas create a new challenge in that if a waterway that flows into an urban area and then out again at the conclusion of the area, the stream order number must be treated as it would have been if it flowed through the area naturally rather than in pipe or drain networks. If waterways flow from a drain network they are not necessarily stream order 1, they are numbered as they would have been if they had continued to flow through the area.

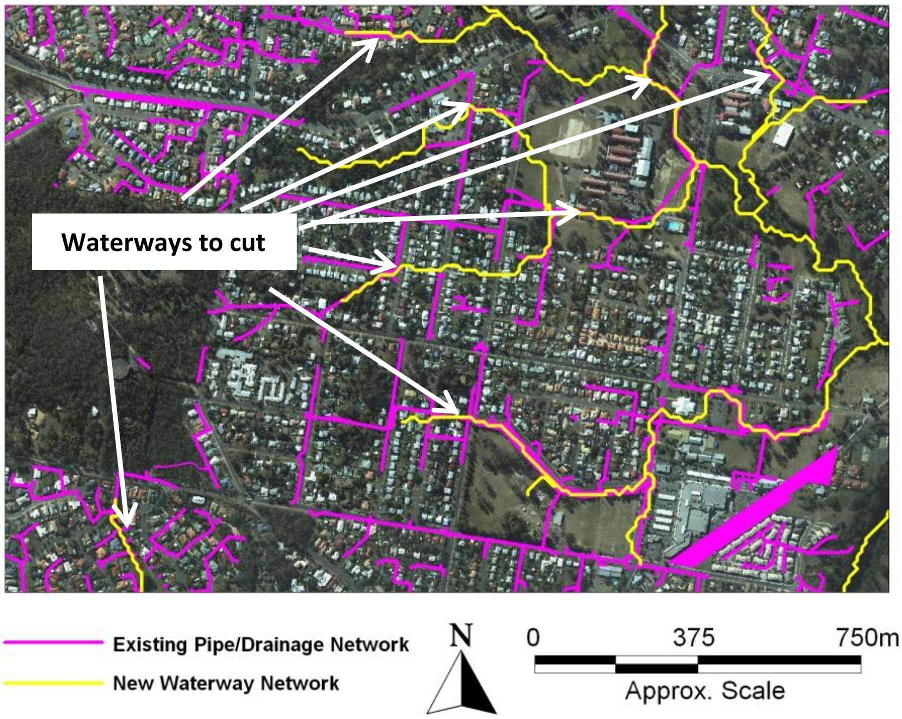

Figure 10: Example Waterways to Cut

3.9 Ground Truthing

Finally, waterway results were compared with 0.1 m² aerial imagery to ascertain the accuracy of the new waterways data with the natural waterway systems evident in the imagery. The computer generated digital waterways were then both screen and ground truthed in areas around the Ipswich City Council local government area. Initially the waterways were screen truthed to assess accuracy of the new waterways and later in further assessment, Ipswich City Council staff field ground truthed the data in accessible areas. Implications of this ground truthing are that waterways can be "ground truthed" digitally more effectively and efficiently than by spending large amounts of unnecessary time in the field.

4 RESULTS

As described in 3.3 to 3.8 various analysis tests were conducted to create data for this work. Results from the testing, analysis and ground truthing are displayed in this section, it includes catchment input parameters, lengths of waterways from those input parameters, and comparisons of the new data sets with the 2004 waterway network.

Figure 11 illustrates the location of the stream ordered networks from the 2004 and 2012 data with different catchment resolutions.

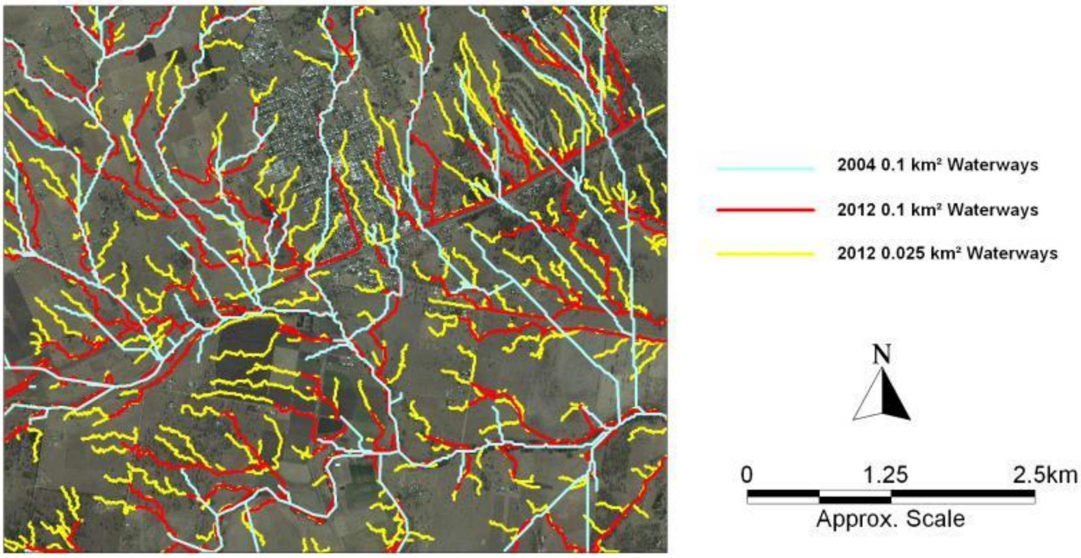

Figure 11: Variations in Waterway Locations

4.1 Catchment Input Areas

Figure 12 compares the total lengths of waterways created using the 0.1km^2 and 0.025km^2 input catchment areas.

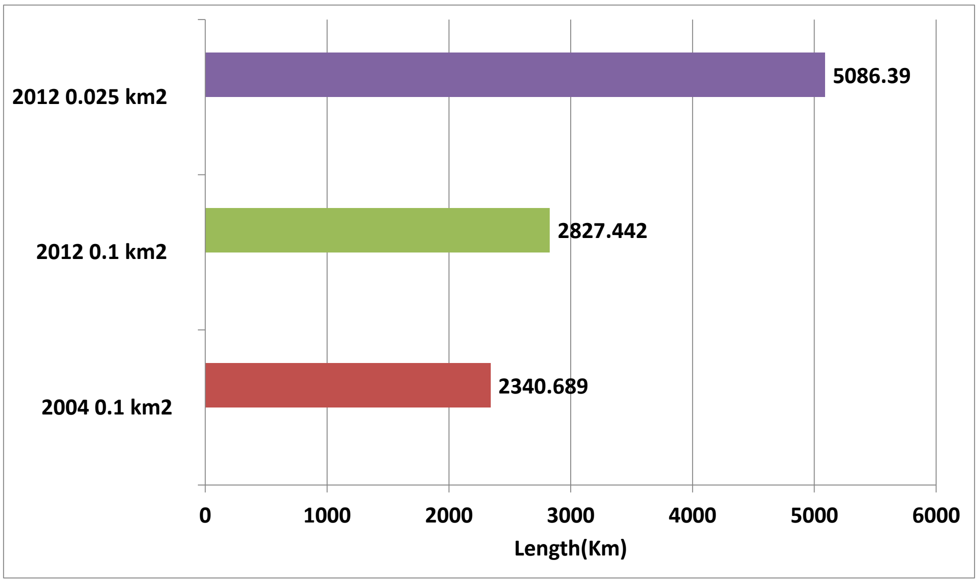

Figure 12: Overall Waterway Lengths from the Various Catchment Input Resolutions

Figure 13 displays total lengths of stream ordered waterways in the ICC area. It displays a consistency of higher lengths of waterways for each stream order and comparison of lengths between the three studied data sets.

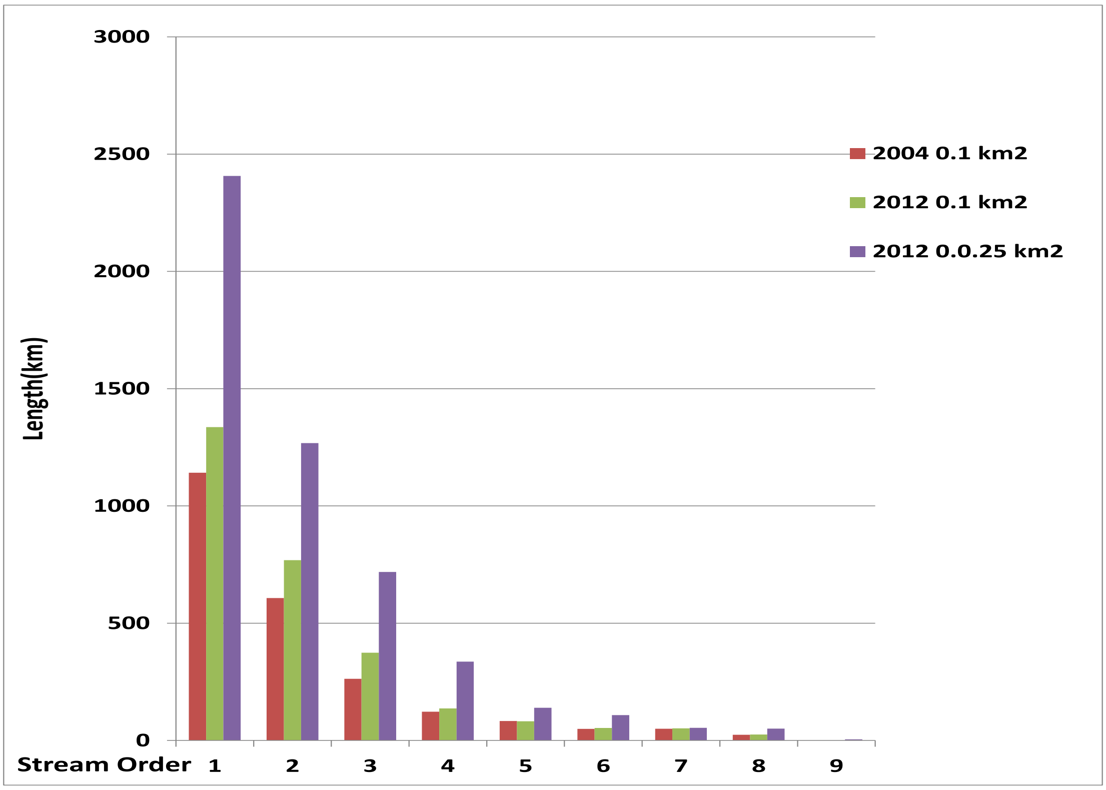

Figure 13: Total Length of Stream Ordered Waterways0.1km2 and 0.025km2 catchment input areas

Figure 14 displays total lengths of stream ordered waterways in the ICC area with a consistency of higher lengths of waterways (particularly for smaller stream orders) and it also displays comparisons between the three studied data sets.

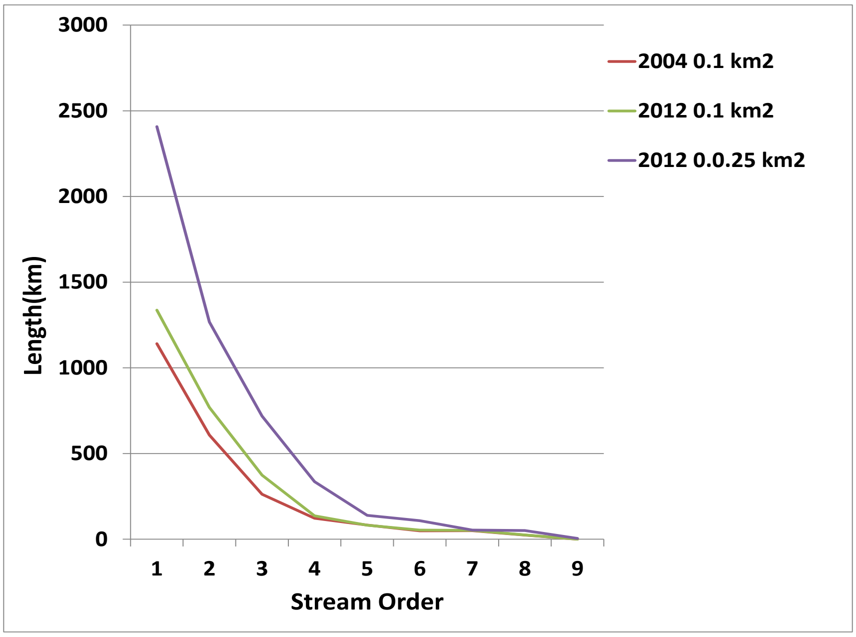

Figure 14: Total Length of Stream Ordered Waterways, 0.1km2 and 0.025km2 catchment input areas

5 DISCUSSION

5.1 Visual Similarities of Derived Data

Waterways created from different resolutions DEMs can appear similar. Figure 15 shows waterways created using different catchment input resolutions look similar, but are in fact quite different in their lengths. Figures 12, 13 and 14 show numerical results derived from what appear to be similar waterway networks. For instance, the 0.1 km² input creates approximately half the length of waterways in the similar looking 0.025 km² derived waterways. This variation, in what looks to be similar data, can have significant impacts on something as simple as estimating costs of remediation of waterways.

Cost of remediation of waterways displayed in Figures 7, 12, 13 and 14 vary considerably with change in detail of a derived waterway network. The 2012 0.025 km² catchment input waterways, waterways with the smaller catchment input creates twice as many waterways (in kilometres) as the two networks derived at 0.1km². Estimation for cost of remediation would therefore be twice as much. The 0.1 km² waterways from 2004 and 2012 have similar extents, but the 2004 data is smoother based on being created from a less detailed DEM.

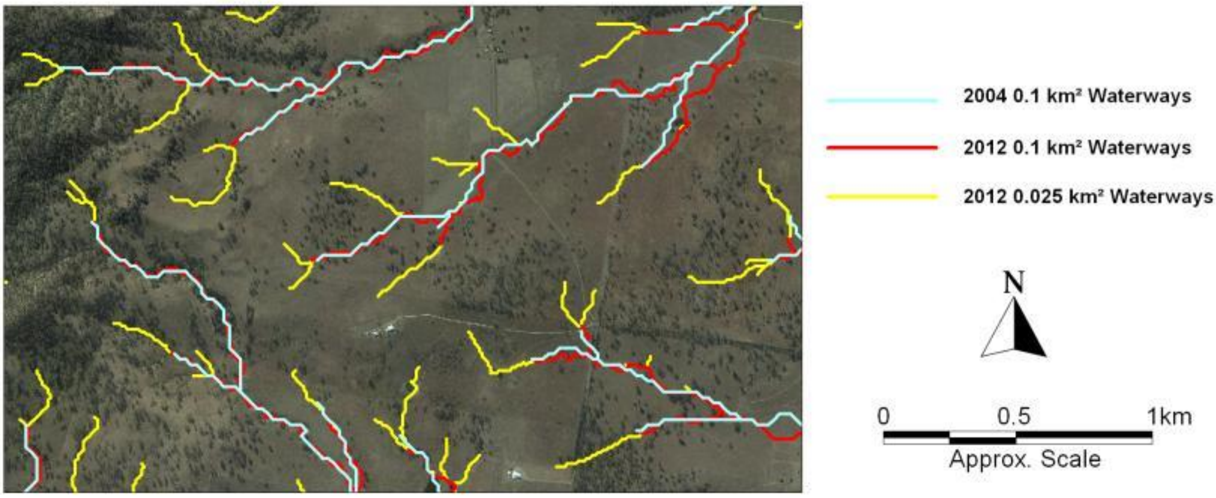

Figure 15: Lengths of Waterways for Estimation of Buffer Zones

Over the entire local government area there is approximately a 20% increase of waterways lengths between the 2004 and 2012 0.1km² waterways, the zoomed (5.2km²) example in Figure 15 and Table 3 shows around a 10% increase in this small area.

Table 3: Lengths of Waterways from Figure 14

Year	2004	2012	2012
Catchment Input Area	0.1 km²	0.1 km²	0.1 km²
Length (km)	9.88	10.88	19.35

5.2 Grid Size and Catchment Input Resolution

Change in grid resolution, particularly when combined with the added benefit of more detailed raw data, enhances the quality of waterway created from the DEMs. The more detail displayed in a surface, the more detailed the waterway network created from it. Grids of the same size can also give different results as displayed in Figures 12, 13, 14, 15 and Table 3. Waterways derived from 2004 and 2012 DEMs at 0.1 km² catchment input resolution show that if raw data is of a different quality, results can be different. Two 20m DEMs with the same catchment input resolutions can have quite different waterway length results, (See Figures 13, 14 and Table 3). Catchment Input resolution greatly varies the length of waterways within a study area.

5.3 LiDAR Inaccuracies and "Traditional" DEM data

Despite the improvements in terrain data such as LiDAR, inaccuracies still occur. Built objects such as bridges and culverts can appear and act as dams in a DEM. Subsequent stream order processing treats the road as a dam, pit fills behind it and the derived waterways can flow the wrong way. Figure 16 displays the 2004 waterways created from the "traditional" 5m contour data (without the road/culvert) and the 2012 waterways created from Lidar data (with the road/culvert). The DEM inset shows the road appearing as a dam and why it would be pit filled if left in a DEM.

Therefore, it is possible that waterways can be created from a LiDAR derived DEM and be incorrect simply based on a lack of local knowledge by the creators of data. This is particularly evident over a large area such as in this study. Not having local knowledge of an area could result in inconsistencies, or incorrect waterway data to remain in use. Derived waterway vector line work data needs to be corrected manually or the DEM needs to be modified ("dams" removed) prior to pit filling to ensure drainage flows in the appropriate direction.

In general, because of the accuracy of the data, the Lidar data and the DEM derived from it are suitable for waterway development. Waterways extracted from the 10m Lidar DEM also considered suitable for this work.

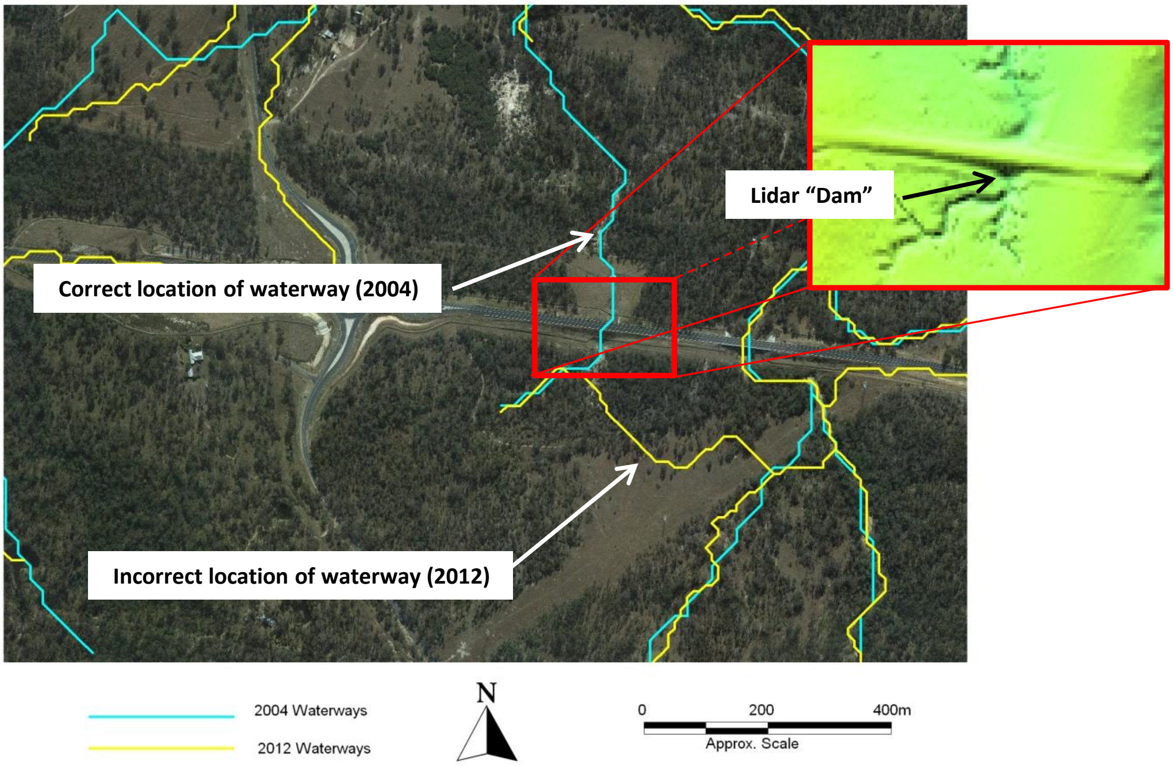

Figure 16: Lidar Dams

5.4 Software Capability Improvements

Waterway creation is governed by the size of the input grids, which are in turn governed by the capabilities of the original grid creation software. The original 2004 waterways used in the (Harris 2008) work were created using Vertical Mapper software which can process processes approximately 2 million points. The Discover software can handle approximately 1 billion points, which allows for much larger DEM creation. Nevertheless, Discover cannot necessarily pit fill and create waterways from the DEMs it allows to be created (as evidenced by being unable to process waterways from the 5m DEM in this work). Software such as TAUDEM used earlier in the 2004 work was at that time limited in its ability to process large data sets.

5.5 Applications for Use

Waterway lengths for this work were based on the required use of the created waterway datasets. The new Lidar based DEM created extra lengths of waterways using the same 0.1km ^{2} input definition compared to the 2004 study, simply based on being better quality DEM data. This methodology was accepted as still being the best for overall measurement of waterways for estimation of lengths of waterway for remediation and general location of waterways within the ICC boundary.

Total lengths of waterways from the 0.025km^2 catchment input are to be used by the Ipswich City Council for highly accurate work such as waterway run-off and flood studies. This evaluation of a waterway can be created from more detailed DEM data and may not appear on aerial imagery looking like a waterway.

However, costs for stream remediation areas based on lengths could be over-estimated by higher resolution waterways such as those created from the 0.025 km^2 catchment input resolution. Figure 15 shows an example of waterway lengths that could be used for estimation of buffer zones. The cost of remediation is based on the general length of waterways and highly accurate polylines of waterways such as those created for the 0.025 km^2 waterways will give a large over estimation of lengths for that purpose.

6 CONCLUSIONS

Improvements in data and software capabilities have allowed advances in the mapping of waterways using GIS. This allows for the study of larger areas and for improvements in processing speeds, along with improvements in data derived. The area studied in this work was unable to be processed at this scale just a few years ago. It is concluded that DEMs created from LiDAR data allow for the delivery of accurate waterways. The higher the accuracy of the elevation data, the better the quality of output data (such as waterways). A LiDAR derived DEM allowed for the determination of the most appropriate waterway network of the 1096 km^2 study area.

The work showed that, in an area such as the Ipswich City Council, improved waterways created from LiDAR data are suitable for use on a whole of local government area basis, albeit with a requirement for two stream ordered networks. One network (0.1km^2) for general waterways locations and lengths, and another more detailed (0.025km^2), network for detailed assessment of water run-offs and flood studies. The use of two waterway networks is new for the Ipswich City Council, and should perhaps be considered in other areas where detailed modelling is required.

Another implication of this work is the acceptance of the 0.025km^2 input catchment derived waterways being acceptable for use is the ramifications when considering the data in conjunction with regional scale data that is only mapped at 0.1km^2 catchment input area. The stream ordering of the more detailed data does not match the surrounding region and therefore is only used for work within the Ipswich City Council area.

The work also showed that assessment on such things as waterway remediation based on the 2004 waterways networks were under estimated by approximately 20%. Based on work in this study, it may be possible to apply the percentage difference in other parts of South East Queensland that use the 2004 waterways network as base to allow for a more accurate assessment of waterways lengths within the catchments and local government areas of the region.

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