CHAPTER 12

Deriving Hydrological Networks in the Maltese Islands for Flood Risk Assessments - A Comparative Study

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Introduction

One of the most significant effects of urbanisation is the increase in impervious surface cover which reduces infiltration and increases runoff volume. Effective management of urban storm water runoff and water quality issues can only be accomplished once drainage area and flow networks are accurately identified (Parece and Campbell, 2014). Water resources cannot be properly managed unless their spatial distribution is known, in terms of quantity and quality, and how these variables are dependent on the parameters of periodic events, such as the intensity and duration of storms. Data from hydrological networks are used by public and private sectors for various applications, including planning of water management systems, the preparation and distribution of flood forecasts and warning systems, and the design of spillways, bridges and culverts (Stewart, 2015).

A good understanding of the hydrological functioning of suburban areas can contribute to reducing flood risks and improving the overall water management as natural land is urbanised (Jankowfsky, Branger, Braud, Gironas & Rodriguez, 2013). Reliable hydrological data and information are key inputs to the sound management of water resources. In particular, knowledge about the drainage system and contributing areas is relevant for drainage and storm water management (e.g. sizing and location of sewer pipes, and construction of hydrological models) (Jankowfsky et al., 2013). Furthermore, the quality and accuracy of data required for a specific hydrological application will depend on the requirements of the application area. For example, where there are life-threatening risks, greater confidence is required in the quality and accuracy of the data (Stewart, 2015).

Theoretical Issues

Deriving hydrological networks

Various methods have been used for the designation of watersheds and their respective water flow lines. On-the-ground surveys in an urban area produce a watershed boundary that is dissimilar to those of a natural watershed because they can account for grading and slope changes from impervious surfaces. However, such surveys cannot account for inflows or outflows due to storm water infrastructure. Furthermore, in large urban areas field surveys can be quite complex, expensive and disruptive to daily human activities (Parece and Campbell, 2014). Extensive research has been accomplished in modelling water flow with the introduction of Geographical Information Systems (GIS), (Rodriguez, Andrieu, & Morena, 2008).

Geospatial technologies include vector and raster analysis, the latter derived from aerial or satellite imagery. GIS techniques enable the user to analyse the spatial distribution of the hydrological data and to derive storm water networks through hydrological modelling. Nonetheless, ground assessments may still be necessary. This is particularly true in urban areas, where structures and landscaping, such as storm sewer networks and impervious surfaces, are designed to redirect water flow and create complex hydrologic geometries (Parece and Campbell, 2014).

Digital Elevation Models (DEMs) provide important datasets for hydrological analysis. DEMs can be used to produce critical topographic and hydrologic derivatives such as slope, aspect and flow accumulation. The accuracy of derived hydrological features is largely dependent on the quality and resolution of DEMs (Li, Tang, Li & Winter, 2013). DEMs may be derived from various height data sources in various forms and formats and can be represented as a raster or as a vector-based triangular irregular network (TIN). DEMs were traditionally acquired through techniques such as land surveying and photogrammetry with relatively coarse resolutions and low accuracies. As an emerging technology, Light Detection and Ranging (LiDAR) has been increasingly applied to produce a new generation of DEMs with higher resolution and accuracy based on laser technology.

LiDAR densely samples the ground surface and produces point clouds with highly accurate three-dimensional positions that can then be used to derive these high-resolution DEMs (Li et al., 2013). LiDAR is considered as a cost effective and accurate method of creating DEMs (Hill et al., 2000). LiDAR-derived DEMs possess higher horizontal and vertical accuracy thereby being more suitable to depict minor topographic variations that control surface water flow across low-relief landscapes (Jones, Poole, O'Daniel, Mertes & Stanford., 2008). For example, LiDAR-derived DEMs are capable of modeling low-order drainage lines and fine-scale headwater channels that were not present on topographic maps or even orthorectified aerial photographs (Li et al., 2013).

The combined use of DEMs and GIS has allowed the implementation of algorithms for automatic watershed delineation. The most commonly used is the d8 flow direction algorithm (O'Callaghan and Mark, 1984) in which the flow direction follows the steepest gradient towards one of eight neighbours. These algorithms are combined with routines to remove sinks, accumulate the flow, extract the stream network and delineate the watershed and subcatchments (Jankowfsky et al., 2013). However, since airborne LiDAR only reflects topographic features, the derived DEMs are topographic DEMs and drainage structures, such as culverts, underground pipes or areas below bridges cannot be detected (Jankowfsky et al., 2013). As a result, in such areas, the modelled water flow and flow accumulation over the land surface would not be an accurate representation of the on-site water flow during a storm event.

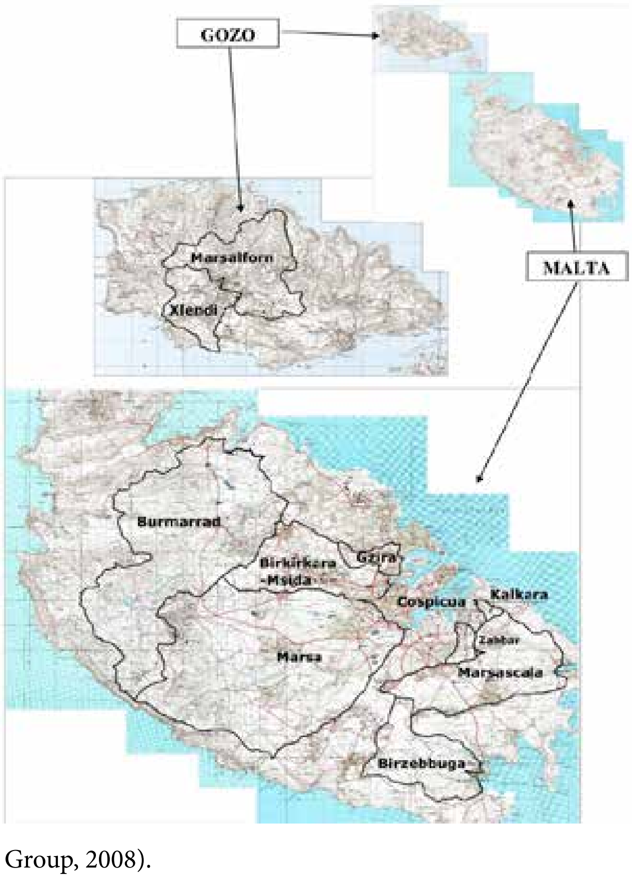
Collection of field data on drainage structures (culverts and bridges) has been found to be necessary for a more realistic hydrological modelling. Li et al. (2013) used such data to create hydrological breaklines to derive a hydrological DEM which allows surface flow through drainage structures that are generally unrepresented in a topographic DEM. Field verification for drainage structures is recommended along with DEMs derived from high resolution data such as LiDAR to estimate more reliable boundary and drainage areas in flat, low-gradient coastal plain landscapes (Amatya, Trettin, Panda & Ssegane, 2013).

The Maltese Scenario

The topography of the main island of Malta has a general West-East dip. The country does not have permanent rivers or streams and surface water runoff temporarily flows through valley systems that are completely dry throughout most of the year and are active only after heavy storm events. Urbanisation is most dense on the lower Eastern side of the islands and by time has encroached on the valleybeds of these natural valley systems with the building of roads and housing. Efforts to control urban sprawl in the last decades has further concentrated around these areas. Furthermore, flooding events in the Maltese Islands have become increasingly characterised by high intensity short duration rainfall events (Ministry for Sustainable Development, the Environment and Climate Change, 2013), which due to the inadequacy or absence of a storm water infrastructure, result in the accumulation of uncontrolled surface water runoff in areas where the valley channel has been urbanised.

This flow occurs for a very short period of time and is mostly concentrated in the valley channels which resume their original natural water conveyance function, irrespective of whether they have been urbanised or not. Fflood risks to life and property are most acute in those segments where the natural valley channel has been urbanised and developed into roads, which is a common situation. A Storm Water Master Plan (SWMP), commissioned in 2006, was aimed at providing sustainable solutions to local flood hazards and at establishing profitable multipurpose water utilisation systems (Tahal Group, 2008). During the SWMP, ten areas which are vulnerable to flooding due to uncontrolled surface storm water runoff were identified (Figure 1), with the largest watersheds (in decreasing size) being Marsa, Burmarrad, Birkirkara-Msida, Marsascala, Birzebbuga and Gzira.

Figure 1: Watersheds as designated in the STWP which are prone to flooding



Source: (Tahal Group, 2008).

Hydrological studies were carried out for each watershed using a rainfall-runoff application modelled on hourly and daily model rainfall inputs, as well as soil type and land use maps. A topographic map with 2.5 m interval contours was used to delimit the watershed area. Design discharge values were determined based on a 5-year storm with a duration of eight hours. Based on model output data engineering solutions, such various hydraulic structures were proposed to mitigate flood risks in areas susceptible to flooding. The Plan also provided alternatives for storm water harvesting from different catchments.

Proposals for a National Flood Relief Project (NFRP) were drawn up on the basis of more detailed technical and economic feasibility studies. The aim of the NFRP was to mitigate flood risk in the worst hit areas. The flood risk areas identified in the SWMP were shortlisted to specific localities in four catchments namely the - Marsascala, Birkirkara-Msida, Gzira and Marsa catchments. A dynamic rainfall-runoff simulation model (EPA-Storm Water Management Model) and a hydrological modelling system (HEC-HMS) were used to simulate the hydraulic characteristics of the uncontrolled surface water runoff resulting from a 1 in 5 year event. The simulation results for the 5 year storm events resulted in the assignment of flood water depths for main roads within each of the catchments. The aim was to optimize the design of the technical options considered under the NFRP for management of this runoff (EEA-EIONET, 2015). A flood damages assessment was also carried out for the 5-year flood simulation, estimating the total damages on a social level, economic losses and damages to buildings and infrastructure (Politecnica Soc. Coop. Consortium, 2010a). Given the extremely short temporal scale of flood events in Malta, no information on the hydrological characteristics of past flood events was ever recorded. Therefore, the probability of the events in the derived flood risk maps is based on rainfall return periods since no direct measurement were available with which to correlate these simulated flood events (EEA-EIONET, 2015).

Acquisition of LiDAR data over the Maltese Islands

The first LiDAR survey over all the Maltese Islands was carried out through an ERDF project entitled ‘Developing National Environmental Monitoring Infrastructure and Capacity’ (Hili, 2014). This technology was a novel source of very high resolution data for the topographic analysis of the Maltese Islands. Prior to this, Digital Elevation Models were derived from aerial orthophotography as provided by the then Malta Environment and Planning Authority. The use of photogrammetric capture methods to collect topographic detail is often laborious, work-intensive, lengthy and hence, costly (Agius & Brearley, 2014). Derivation of hydrological networks for the south-east area of Malta from contour maps and derived Triangular Irregular Networks (TINs) was carried out by Tabone Adami (2001) as part of a hydrological study to quantify storm water and nutrient flows into coastal waters. From the LiDAR data acquired during the topographic LiDAR survey of the ERDF project, Digital Surface Models (DSMs) and Digital Terrain Models (DTMs) were derived.

Methodology

Watershed and drainage networks delineations in the NFRP

As part of the NFRP and based on catchment delineations from the SWMP, the Consultants working on the NFRP drew the water flow lines within sub-basins in each catchment (Politecnica Soc. Coop. Consortium, 2010a). The boundaries of each sub-basin were determined based on the morphological characteristics of the land, natural or engineered canals and slopes and the presence of roads that can constitute a drainage canal, an embankment, or barriers to water flow. The flow direction was then established based on this road network. This process was carried out for the four flood priority areas: the Marsascala, Birkirkara-Msida, Gzira and Marsa basins. Hydrological models were simulated for each sub-basin estimating the peak value for different return periods including that of a 1 in 5 year flood (Politecnica Soc. Coop. Consortium, 2010b).

Watershed and drainage networks delineations from LiDAR data

The aerial survey for the topographic LiDAR scan, as part of the ERDF project, was carried out on the 17th February 2012. This included the acquisition of ortho imagery with a ground resolution of 15cm and a 30cm XY accuracy.

The LiDAR point cloud acquired had an average of 4.3 points/m3 and a height accuracy of less than 10cm. The resultant DSM had a 1m grid resolution and an equivalent height accuracy. This DSM was processed for the hydrological analysis in this paper using ArcToolbox processes in ArcGIS 10. The process using the ArcGIS geoprocessing tools is summarised in Figure 2 and is described further below.

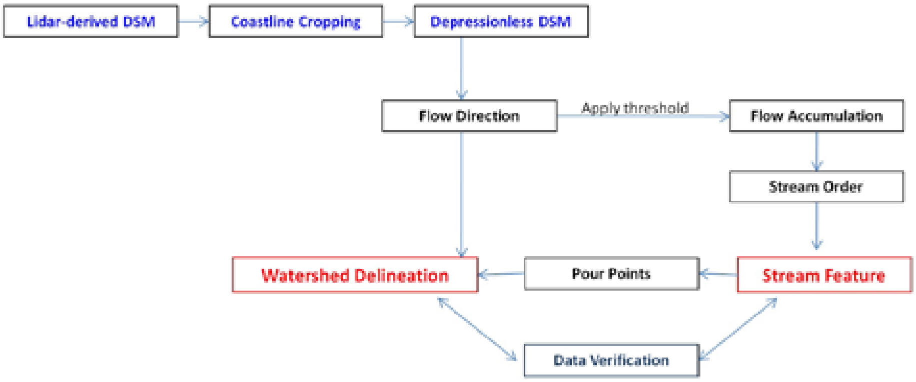
The following steps were implemented for the hydrological modelling:

- Crop sea areas using the coastline polygon as a mask;
- Prefill of spurious artifacts in the DEM to create a depressionless DSM. Small sinks were regarded as spurious artifacts resulting from errors caused by artifacts of DEM interpolation;
- Derive flow direction using the depressionless DSM as an input;
- Derive flow accumulation from the flow direction raster. A cell value in the flow accumulation raster is the number of upstream cells flowing into the cell;
- Apply a threshold of flow accumulation. Based on various outputs, a threshold value of 1500 was applied to realistically represent relevant parts of the hydrological networks. Any raster cell with an upstream area greater than the 1500 threshold

was selected as part of the network. The orthoimage was used as a reference background layer in the GIS to better interpret the location of the hydrological network;

- Create a stream order by assigning a numeric order value to the flow accumulation raster above. Streams with a high order have higher water flows. Six stream orders were derived with order 1 being the lowest accumulation level to order 6 with the highest accumulated water flows;
- Convert the stream order raster to a stream feature map. Each stream order feature was assigned a unique map symbology;
- Identify pour points to delineate the contributing watersheds. A watershed is the upslope area that contributes water flow to a common outlet - the pour point. Pour points were identified only for networks which contained orders equal or greater than 3;
- Delineate watersheds using the flow direction map and the location of the pour points; and
- Verify network with NFRP drainage networks and field data.

Figure 2: Methodological process for the derivation of hydrological networks from the DSM



Comparison and verification of networks

For the purpose of verification of LiDAR derived data, comparisons of the drainage network and corresponding watersheds were applied to the areas of the four catchments investigated in the NFRP. These pertain to the Msida, Gzira, Marsa and Marascala catchments. In the case of the Msida, Gzira and Marsa catchments, comparisons were made between the water flow routes depicted in the NFRP study and the LiDAR-derived networks. Furthermore, an additional field survey of the stretch of watercourse between Zabbar and Marsascala, was carried out during April 2016, as a case study for this chapter. The area of study included sections of the watercourse that are still in a relatively natural state, ranging from little or no vegetation cover to fully vegetated areas, together with other stretches that have been heavily modified by the construction of roads, culverts and sumps. The field survey included detailed site observations at specific locations where the LIDAR data derivations had been noted to be incomplete or incoherent with the overall hydrological network modelling of the catchment.

The field survey also included the gathering of local knowledge about water flows during storms and the identification and recording of physical features that clearly alter the flow of surface water flow, which features, can easily go undetected by the LIDAR data derivations. Such physical features included underground pipes, culverts and connecting sumps as well as low walls and outlets intended to keep water out, or divert it, where there are changes in ground levels. The site-specific survey enabled a comparison of the whole stretch of the network with the LiDAR-derived network and was instrumental in identifying and understanding the sources of errors more comprehensively. Underground and overhead hydrological features such as culverts and bridges cannot be identified solely by LiDAR data.

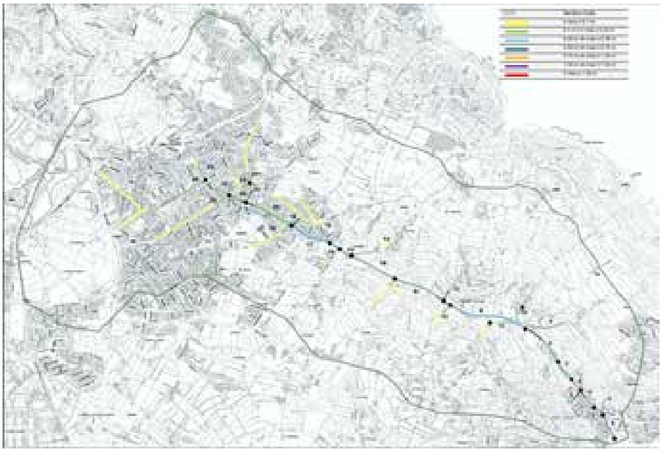
It was concluded that field surveys denoting such hydrological features are key to correct the LiDAR-derived hydrological network. Through the collected field data, including mapping of routes, the location of culverts, sumps and underground tunnels, and knowledge of the site during storm events, shortcomings in the LiDAR-derived network were identified. The LiDAR-derived hydrological network for the Marsascala catchment was then edited to conform to the verified flow as a remedial measure.

Results

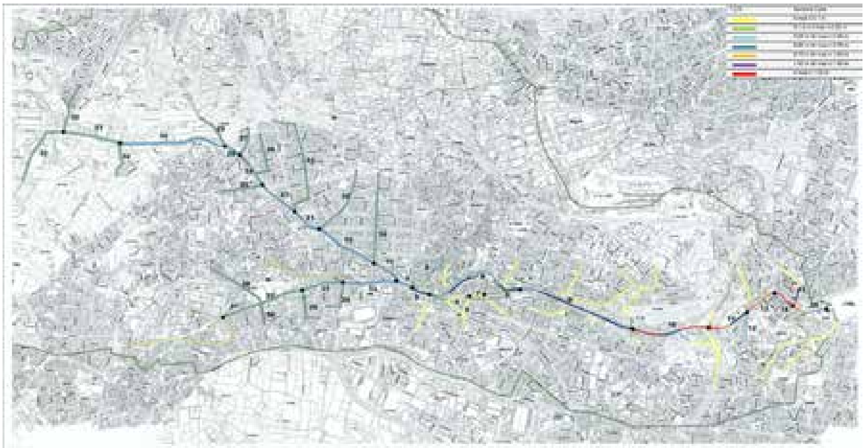
Comparison of catchment networks

Maps of the watershed boundaries delineated during the NFRP study and the respective water depths of flooded routes are shown for the four catchments (Figure 3). Water depths represent the result of the hydrological simulations for a 5-year recurrent storm event. The simulated water depths for each inundated road and the survey code of each road section are indicated.

Figure 3: Watershed boundaries, flood simulation water depths and survey codes as delineated in the NPRP study for (a) Marsascala (b) Birkirkara-Msida (c) Gzira (d) Marsa catchments



(a)



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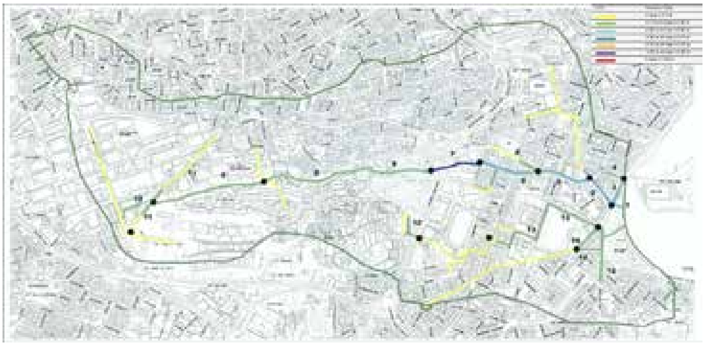

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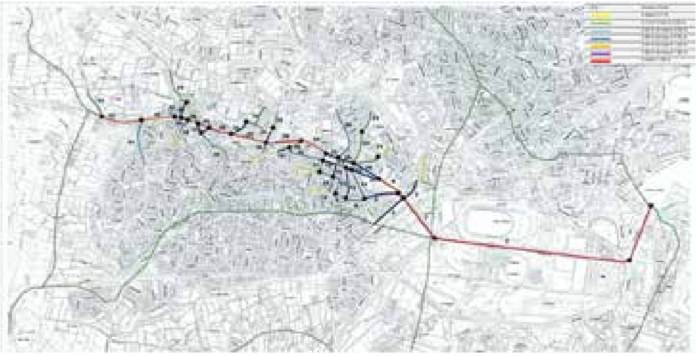
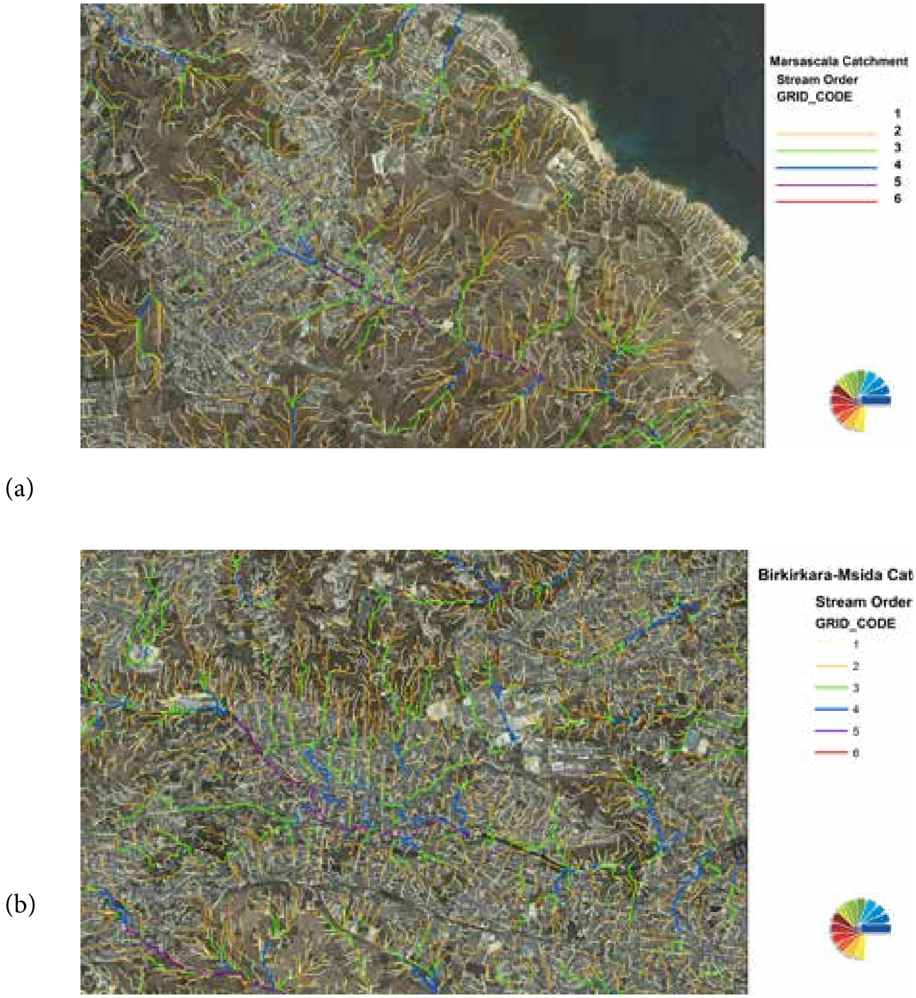


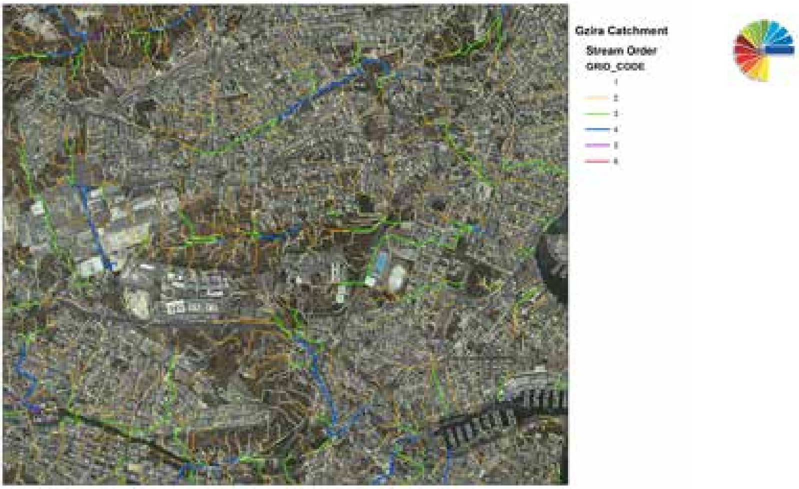
(d)

Source: (Politecnica Soc. Coop. Consortium, 2010a)

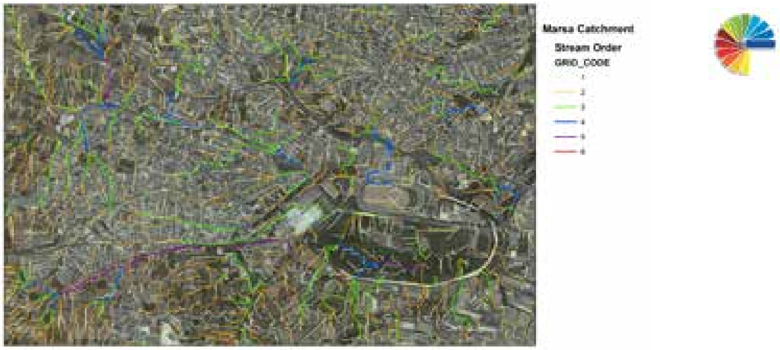
The stream networks derived from the LiDAR DSM for the four catchments are shown in Figure 4. Stream orders are colour coded. The maximum stream order achieved was order 6 in the case of the Marsa catchment, thereby being the most extensive network,

Figure 4: Stream networks derived from the LiDAR data for (a) Marsascala (b) Birkirkara-Msida (c) Gzira (d) Marsa catchments





(c)



(d)

Overall comparisons of the stream networks derived from the NFRP study and those derived from LiDAR DSMs demonstrated a good comparison overall with respect to the main flow directions. The networks derived from the LiDAR DSMs were more extensive given that each 1m x 1m pixel in the DSM was taken into account in the hydrological model. The NFRP networks were established only on those land areas for which field surveys were carried out and were based on expert judgement of the area.

Marsascala basin - The NFRP study estimated the Marascala basin to be about 4 km2 with the highest point of the watershed located in Zabbar, 57 m above sea level and the lowest site being Marsascala Bay at sea level (Figure 3a). (Politecnica Soc. Coop. Consortium, 2010a). The stream network derived from the LiDAR DSM denoted a stream order of 5 as the largest order commencing from Zabbar (Figure 4a). The main network derived from the LiDAR DSM follows the same overall route as that denoted in the NFRP study but is disjointed at some points along the Zabbar-Marsascala agricultural area. The LiDAR-derived network also derived the contributing tributaries since the model takes into account all the catchment surface area.

Birkirkara-Msida basin - Through the NFRP study, the watershed area of the Birkikara-Msida basin was estimated to be about 11 km2 with the highest point of the watershed located in Naxxar, 128 m above sea level and the lowest site being the Msida Marina at sea level (Politecnica Soc. Coop. Consortium, 2010a). In the case of a 5-year recurrent storm event, about 12 km of roads were calculated to be inundated starting from Valletta road and Naxxar Road in Birkirkara, along the main axis in Valley Road until Msida square (Figure 3b). Figure 4b shows the stream order created based on the LiDAR DSM. The main network follows the same path as that denoted in the NFRP study. A stream order of 5 was the largest order commencing from Birkirkara and ending at the top part of Valley Road due to the presence of a depression in that area. Beyond that area, the hydrological model from LiDAR data continues to follow the same route as that in the NFRP data and identifies the tributaries contributing to the main network up to stream orders of 4.

Gzira basin - The NFRP study estimated the watershed area of the Gzira basin to be about 2 km2 with the highest point of the watershed located in San Gwann, 100 m above sea level and the lowest site being the Sliema Creek at sea level (Figure 3c) (Politecnica Soc. Coop. Consortium, 2010a). In the simulation, 4 km of roads were calculated to be inundated starting from San Gwann industrial estate down to Gzira. The network from the LiDAR DSM (Figure 4c) denoted two main networks, one of which follows that located in the NFRP study. This LiDAR network had a maximum stream order of 4 commencing from San Gwann although the network is disjointed in the Gzira area after Wied Ghollieqa. The second main network in the upper part of the catchment, also with a maximum stream order of 4, coincides with the northern border of the Gzira basin delineated in the NFRP study. The LiDAR network also includes the presence of various smaller subsidiaries not connected to the main network of this basin.

Marsa basin - This was the largest basin investigated in the NFRP study with a watershed area of about 47.6 km2. It comprises two main watercourses (Kbir in the south and Sewda in the north) that join before entering Marsa with the largest part of the basin being agricultural land (Figure 3d). The highest point of the watershed is located in the Ġebel Ciantar area at 216 m above sea level and its lowest site is the Marsa Creek at sea level. The watershed's longest water course length running from southwest to northeast is about 12 km. Once again the stream network derived from the LiDAR DSM is extensive given that the non-urban areas are considered in the model (Figure 4d).

Two major networks with a maximum stream order of 5 are indicated. However, particularly over the Qormi and Marsa border (beneath the Marsa racetrack), disjoined networks are visible. Investigation into the LiDAR DSM data over these areas showed that these areas pertain to DSM pixel values of NO DATA in areas of low water reflectivity (Figure 5). These include areas of standing water such as swimming pools, open reservoirs and water retention areas following heavy rainfall, such as areas in Wied is-Sewda, upstream of Qormi (Figure 6a). The latter was the case given that the LiDAR survey was carried out after a recent storm. Pixels with NO DATA were not taken into account by the hydrological model, thereby deviating the real course of the hydrological network.

Figure 5: Stream networks derived from the LiDAR data for over the Qormi-Marsa area overlaid on DSM. White patches represent areas of NO DATA.

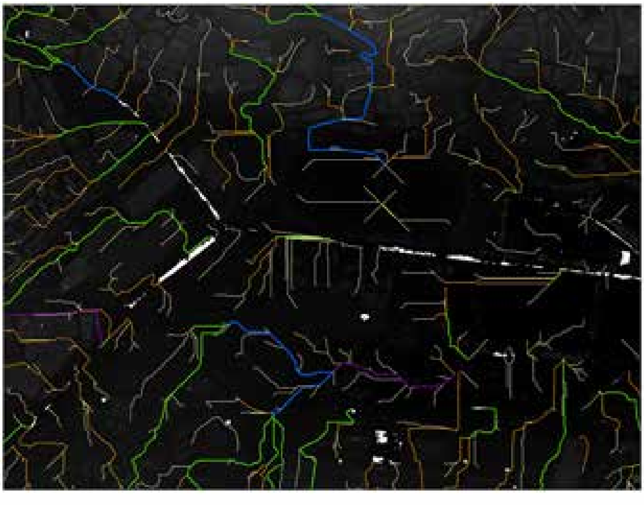
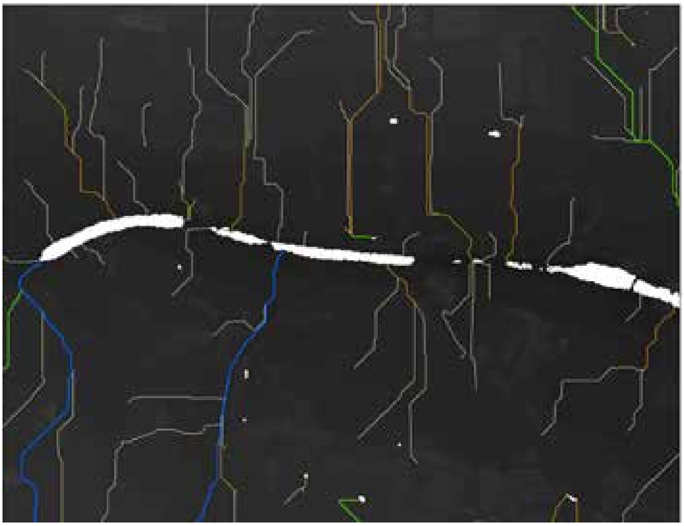


Figure 6: Effect of standing water areas on DSM (a) flooded areas in Wied is-Sewda Qormi, within the Marsa basin (b) corresponding areas of no reflectance of LiDAR data shown in white.

(a)

Source: Works and Infrastructure Department, Malta

(b)



Marsascala catchment - comparison with field survey

The field survey carried out along the Marsascala catchment helped to investigate the LiDAR-derived network in greater detail. Overall, the main network from the LiDAR data compared favourably to the field survey and knowledge of the watercourse from expert knowledge. However, the following shortcomings in the LiDAR-derived networks were identified.

1. Presence of false pits. As noted in Figure 7(a), the network is broken at points 1 and 2. The location of a false pit (a field below road level and a swimming pool in this case) and the presence of a physical barrier in the road-field boundary wall diverted the network to the pit. Therefore the two points had to be joined manually to continue the network along the road (where the water flows at a higher level from the adjacent land), as substantiated by the field survey. The subsequent stream orders reclassified to order 5 so as to continue with the same order downstream (Figure 7b).

Figure 7 (a): Diversion of stream network in the Marsascala catchment caused by a false pit (b) result of editing to join stream network along stream order 5 (shown in voilet).

(a)

(b)

2. Presence of canopy cover along the route. Through field data and on-site knowledge, it is known that the water is diverted into the valley bed through a manmade passageway enroute (Figure 8) at point 3 (Figure 9), moves along the valley vegetation, across a weir and flows into a sump. Water from the upper part of the Marsascala-Zabbar valley flows along the main road through point 4 and joins the flow from the valley vegetation.

Since a DSM includes both building and tree heights, the presence of the tree canopy implied increased height levels in the DSM. This precluded the hydrological model from routing the water along the grass under the tree cover (light blue route in Figure 9). For future use, the use of a Digital Terrain Model (DTM) data from the LiDAR survey, implying a bare-earth Digital Elevation Model, could be used in those areas for which water flows beneath tree canopies, potentially employing the last return emanating from the LiDAR scan.

Figure 8: Manmade passageway for the diversion of water flow from the road into the natural valley bed. Location refers to Point 3.

Source: Valley Management Section, Works and Infrastructure Department, Malta

Figure 9: Diversion of stream network into the valley bed and along man-made hydrological features. The edited route in shown in light blue.

3. Presence of hydrological features deviated water underground. Since underground hydrological features are not identified through the LiDAR survey, the location of these features is required through field knowledge. These include the presence of various culverts, sumps, bridges and road gratings (Figure 10). As remedial measures, the route network needs to be verified through a site reconnaissance exercise and then edited manually in these locations so as to reconcile the data with the relevant order network derived from the LiDAR DSM.

Figure 10: Man-made hydrological features present along route network (a) road gratings (b) sump

(a)

(b)

Source: Valley Management Section, Works and Infrastructure Department, Malta

4. Presence of NO DATA in LiDAR DSM. Since the LiDAR was carried out following a rainfall event, the presence of large puddles and flooded areas, particularly on impervious surfaces such as roads, led to corresponding areas of no reflectance of the LiDAR pulse. This resulted in areas of NO DATA in the resultant DSM. Therefore, the hydrological model routed the water networks incorrectly in this area (Figures 5 and 6b). The detection of points in water areas is difficult since a laser scanner does not have reflectance of the water, particularly when they are standing waters. Some reflectance of the water is possible when there are some waves or some objects above the water surface. Semi-automatic extraction of water bodies have been investigated to model water areas for DEM generation (Korzeniowska, 2012).

Due to these shortcomings, the route network was disjoined at specific locations. Hence this resulted in gaps within the watershed delineations due to disconnected networks.

Spatial datasets for future flooding models

The use of a hydrological network has extensive applications in terms of its use for simulating rainfall-runoff models. Once the LiDAR-derived network has been edited in locations where the shortcomings were identified, the derived product would serve as an input into the hydrological model. The use of a Geographical Information System (GIS) technology to analyse the datasets of such spatial data is crucial for running flood simulation models. This would include additional spatial data layers as model inputs including land cover and soil type. The use of satellite imagery for the derivation of these datasets provides synoptic data based on the reflectance characteristics of the ground. Overall the flood simulation models can be used to update the NFRP-derived economic and infrastructure effects of flooding.

Conclusion

This study investigated the use of a high-end technology such as LiDAR to derive hydrological networks for all the Maltese Islands by assessing data for four catchments. Overall the LiDAR-derived network compared favourably to the data for the SWMP and NFRP basins. Since the LiDAR survey was carried out for all the Maltese Islands on the same day, it enabled a snapshot overview of the hydrological network for the entire territory including smaller catchments. The use of aerial orthoimagery as a basemap in the GIS enabled the location of network areas under investigation.

Data assessment highlighted shortcomings in some of the LiDAR data. The use of on-site collection of data and site knowledge is a pre-requisite for understanding the network comprehensively and in detail. This is needed prior to applying any specific remedial measures to correct the LiDAR-derived data. Integration of spatial datasets to form a more robust model for flood simulation should be looked on as the next step. This would include the use of satellite imagery as well as future high-resolution and also oblique LiDAR surveys to provide updated digital datasets for hydrological modelling.

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