23rd International Congress on Modelling and Simulation, Canberra, ACT, Australia, 1 to 6 December 2019
mssanz.org.au/modsim2019

Estimating bankfull channel geometry, dimensions and associated hydraulic attributes using high resolution DEM generated from LiDAR data

B. Fentie

Department of Environment and Science, Queensland, Australia
Email: banti.fentie@des.qld.gov.au

Abstract: Knowledge on river channel dimensions at bankfull flow is essential for flood forecasting, stream rehabilitation and bank stabilization works, environmental flow modelling, and streambank erosion modelling. The difficulty of collecting spatially distributed, high-resolution data on channel form and behaviour made it necessary for broad scale erosion models to adopt generalised approaches to bankfull flow estimation. These techniques are commonly based on simple hydraulic formulae applied to cross-sectional averages. It is recognized that these generalised estimations frequently fail to describe the non-uniform flow and transport conditions observed in natural rivers. Application of Dynamic SedNet in the catchment water quality modelling project of Paddock to Reef Integrated Monitoring, Modelling and Reporting Program (P2R) under Reef Plan uses relationships between channel width and height with contributing catchment area that are regionally generated to determine these river channel dimensions. There are obvious shortcomings of this approach including: (1) the fact that channel dimensions are greatly spatially variable even when values of the explanatory variable are the same (e.g., bankfull flow occurs more often on coastal plains), (2) limited data points used to generate the empirical equation. However, with recent advances in the area of generating high resolution digital elevation models (DEMs) from Light Detection And Ranging (LiDAR) data and availability of tools to process them, it may be possible to determine channel geometry and dimensions in a more robust and reliable way. Conventional topographic LiDAR, such as that used to generate the DEM used in this study, does not penetrate water bodies. In these situations, water penetrating LiDAR (Bathymetric LiDAR) will need to be employed. However, in low flow situations, as in the current study, and/or where flow depth can be determined from monitoring, it is possible to subtract flow depth from the water surface elevation to estimate channel-bed elevation and height.

This study demonstrates how a high resolution DEM generated from LiDAR data in conjunction with estimates of flow depth, which was low at the time of LiDAR data acquisition, can be used to generate bankfull river channel width and height thereby allowing estimation of other river flow parameters. Figure 1 shows the workflow (steps followed) in order to achieve this.

Bankfull flow parameter values estimated from the approach currently employed in P2R and those estimated in this study (e.g. flow cross-sectional area, wetted perimeter, and hydraulic radius) have been compared at two modelled stream reaches where LiDAR DEM is available. The comparison shows that the P2R approach overestimates all bankfull flow attributes. However, since Dynamic SedNet uses a user-specified recurrence interval to determine bankfull discharge and applies a calibration coefficient for adjusting bank erosion, the model may not necessarily overestimate streambank erosion. Nevertheless, the reliance on a calibration coefficient to account for input data limitations reduces confidence in model predictions, as it could lead to situations where the model gives the right answer for the wrong reason which will inhibit parameter transfer outside the calibration dataset.

This paper has: (1) demonstrated that the approach adopted in this study using LiDAR DEM may be a more reliable alternative than determining river channel dimensions as a power function of catchment area, and the application of the concept of recurrence interval in estimating bankfull flow, and (2) shown that the assumption of rectangular river channel geometry in the application of Dynamic SedNet in P2R is overestimating bankfull flow and associated hydraulic attributes such as hydraulic radius in the case study reaches.

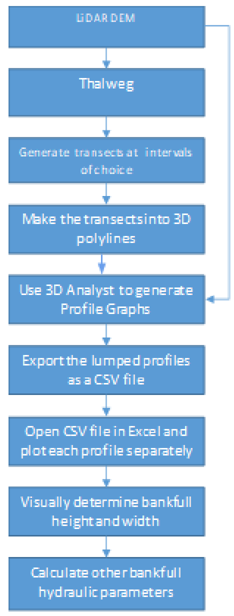

Figure 1. Workflow for estimating river channel dimensions from LiDAR DEM

Keywords: *Channel dimensions, Dynamic SedNet, hydraulic parameters, Mary Catchment*

1. INTRODUCTION

Knowledge on river channel dimensions at bankfull flow is essential for flood forecasting, stream rehabilitation and bank stabilisation works, environmental flow modelling, and streambank erosion modelling. The difficulty of collecting spatially distributed, high-resolution data on channel form and behaviour made it necessary for broad scale erosion models to adopt generalised approaches to bankfull flow estimation. These techniques are commonly based on simple hydraulic formulae applied to cross-sectional averages. It is recognized that these generalised estimations frequently fail to describe the non-uniform flow and transport conditions observed in natural rivers. Application of Dynamic SedNet in the Paddock to Reef (P2R) catchment water quality modelling project of the Reef Plan uses relationships between channel width and height with contributing catchment area that are regionally generated to determine these river channel dimensions. To alleviate this problem, power-law relationships that are unique to the hydrometeorology of the catchment have been used to estimate River channel width (W) and channel height (H) as a function of mean annual discharge (Q). These relationships can also be expressed with respect to contributing area (A) instead of discharge (Q) (Fisher et al., 2013). The plots of the regression equations for bankfull channel dimensions and drainage area are commonly referred to as regional curves. Regional curves are based on simple regression equations, which use one explanatory variable (e.g., drainage area) to estimate the response variables of bankfull width, bankfull depth, bankfull cross-sectional area, and bankfull discharge.

The estimation of stream channel attributes for the Dynamic SedNet model (Wilkinson et al., 2013, Ellis and Searle, 2014), a plug-in for the Source modelling framework, for the modelling component of P2R is an example of methods that use power-law relationships between channel width and height with contributing catchment area. However, there are shortcomings of estimating these stream channel attributes as a function of just catchment area including: (1) the fact that channel dimensions and hence bankfull flow are spatially variable even when values of the explanatory variable are the same (e.g., bankfull flow occurs more often on coastal plains), and (2) limited data points used to generate the empirical equation. Nevertheless, with recent advances in generation of high resolution digital elevation models (DEM) from Light Detection And Ranging (LiDAR) data and availability of tools to process them (e.g., River Bathymetry Toolkit (McKean et al., 2009), Hec-GeoRAS (US Army Corp of Engineers), FluvialCorridor (Roux, et al., 2015)), it is possible to determine these channel dimensions in a more robust and reliable way. Furthermore, where there is a time-series of LiDAR data, it is possible to estimate soil erosion from elevation differences between resulting chrono-sequential DEMs (i.e., DEM of Difference). However, conventional LiDAR does not penetrate water bodies and additional bathymetric measurements are necessary to complete any parts of a DEM which were under water at the time of the LiDAR acquisition (Smart et al., 2009). On the other hand, for reaches with fairly constant and shallow flow of less than 2 m (which was the case in this study), it may be possible to adopt a constant, representative depth. The average flow depth is then subtracted from the corresponding water surface elevation to give the local bed elevation and thereby the channel height. The bankfull height in this study is then determined visually from the cross-sectional profile of the channel.

With the aim of providing a relative study on the potential use of different DEMs to estimate useful hydraulic information, such as water stage, Schumann et al. (2008) compared water stages derived from LiDAR, topographic contours and SRTM Shuttle Radar Topography mission (SRTM). They found that results from LiDAR were by far the most accurate, despite the fact that, for the flood-prone area in their study, the other two sources of DEMs also performed reasonably well.

One assumption made in Dynamic SedNet is that river channels are of rectangular geometry. However, most natural and man-made channels are irregular or trapezoidal in cross-section. Unlike models such as SWAT and HSPF/LSPC (Bicknell et al., 2001), which assume trapezoidal river channel cross-section, Dynamic SedNet adopts a rectangular channel cross-section to model stream bank erosion. This study will demonstrate differences in the magnitudes of different channel attributes with and without this assumption.

The objectives of this paper were twofold:

1. demonstrate that, where it is available, application of LiDAR DEM may be a more reliable alternative than the current approach adopted by P2R when informing Dynamic SedNet of river channel dimensions and bankfull flow estimation, and

2. show that the assumption of rectangular river channel geometry in Dynamic SedNet overestimates bankfull flow and associated hydraulic attributes such as hydraulic radius in the case study reaches.

2. METHODS

2.1. The study area

Covering a total area of some 9,420 km², the Mary River catchment (see location in Figure 2) has a sub-humid and subtropical climate. Average annual rainfall varies from about 2,000 mm/yr in the far southeast, to about 800 mm/yr in the west. This study was undertaken on a 26-km section of the middle reaches of Mary River, between its confluences with Wide Bay Creek and Munna Creek. The adopted middle thread distances (AMTDs) for these stream junctions are 136 km and 110 km respectively. The subject section of the river is highlighted in red in the left map and expanded on the right map (Figure 3).

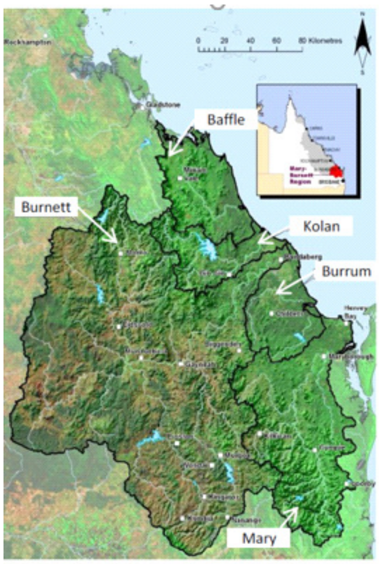

Figure 2. Location of the Mary Catchment in the Burnett Mary region

The Miva gauging station (138001A) is near the middle of the two reaches (modelled links) considered in this study, and is the gauging station with the longest duration of daily discharge data in the catchment (i.e. 2/01/1910 to the present).

2.2. The LiDAR DEM and generation of channel cross-sections

The 1-metre grid bare-earth digital elevation model (DEM) used in this study is derived from airborne LiDAR surveys undertaken in 2009 (Binns, 2017). This LiDAR DEM covers 26 km length of the Mary main channel, and covers two links (SC #489 and SC #636) in the Burnett Mary regional water quality model for P2R. The channel height and width for each of the two links were calculated by averaging the respective channel dimensions of transects within each link. Transects 1-20 (right map in Figure 3) are on link SC #636 while transects 21-52 are on link SC #489.

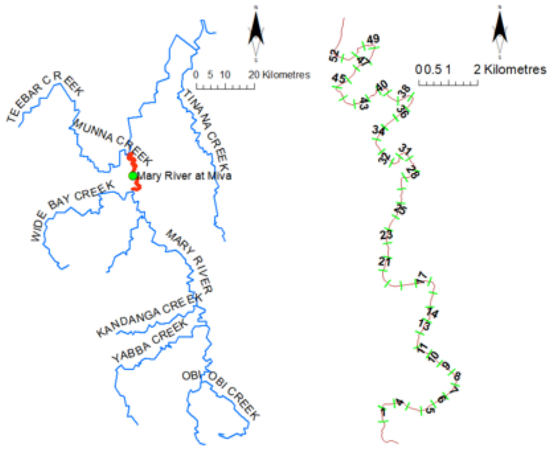

Figure 3. Left: Major tributaries of the Mary River with study reach for this study (red) and location of the gauging station at Miva (green dot); Right: the 52 transects at which channel cross-sections have been generated

The following steps, which are summarized in the workflow depicted in Figure 1, were carried out in ArcGIS to generate 52 cross-section profiles:

1. Generate 52 transects at 500 metre intervals along the study reach using a free downloadable tool called Transect Tool and the River Centreline generated from the LiDAR DEM by Binns (2016) as input
2. Make the transects into 3D polylines using 3D Analyst in ArcGIS and the LiDAR DEM as input
3. Select the Profile Graph button from the 3D Analyst tool bar, which generates a single graph with all the transects plotted on top of each other
4. Export the graphed profiles as a CSV file, and open it in EXCEL
5. Plot each profile using the column 'X' as the x-axis (distance across the transect) and 'Profile i', where i is the transect number, as the y-axis (Elevation)
6. Visually determine bankfull height and width from the plot produced
7. Calculate other bankfull hydraulic parameters such as flow cross-sectional area (A_{bf}), Wetted perimeter (Wp_{bf}), hydraulic radius (R_{bf}) as presented below.

2.3. Determination of bankfull channel dimensions and related hydraulic parameters

Whilst it is beyond the scope of this paper, it may be possible to automate the determination of the point at which the bank will overflow. In this study the bankfull channel dimensions are determined by visually inspecting and deciding on a point on either side of the channel where flow over the bank would first occur. The bankfull width (W_{bf}) and bankfull depth/height (H_{bf}) are then determined as differences in horizontal distance and height, respectively. In the example river channel profile shown in Figure 4 the bank would overflow at the point shown on the right-hand-side of the channel at coordinate (242, 37). The corresponding point on the left-hand-side of the channel is at (98, 37). These two points determine the top width of the channel at bankfull. The lowest point at the channel bed is at (184, 22). One of the limitations of the topographic LiDAR used in this study is that it does not include the depth of water in the channel at the time of LiDAR acquisition. This is clearly seen in Figure 4 where the bottom of the channel has roughly a constant elevation. Therefore, it is critical to estimate the flow depth at that time and subtract it from the elevation of the water surface in order to determine the elevation of the stream bed.

From the three coordinates representing bankfull height on either side of the channel and the thalweg in Figure 4, determined above, it follows that:
H_{bf} = 37-22+2 = 17 m
W_{bf} = 242-98 = 144 m
where the 2 metres added in calculating H_{bf} is the estimated water depth at the time of LiDAR acquisition in this study.

Hydraulic radius is calculated from:

$$R_{bf} = \frac{Area}{W_p}. \qquad (1)$$

Where Area is cross-sectional area of flow and W_p is wetted perimeter.

If a rectangular channel geometry is to be assumed, it would be necessary to convert the channel dimensions determined above to equivalent rectangular channel dimensions with the same hydraulic radius and bank height. With these assumptions, the width of the equivalent rectangular rill (W_{rec}) is calculated from the equation for hydraulic radius as:

$$W_{rec} = \frac{2R_{bf}}{1 - \frac{R_{bf}}{H_{bf}}}. \qquad (2)$$

Bankfull flow velocity (V_{bf}) is proportional to R_{bf} and is calculated from Manning's equation as:

$$V_{bf} = {R_{bf}}^{2/3} \frac{S^{1/2}}{n}, \qquad (3)$$

where S is channel bed slope, and n is Manning's coefficient.

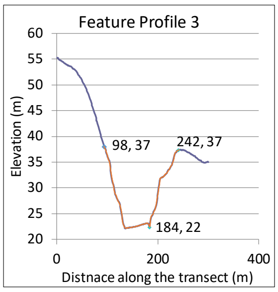

Figure 4. An example cross-section profile (Transect 3 in Fig.2) with the wetted perimeter at bankfull flow in shown in red.

Bankfull discharge (Q_{bf}) is then calculated as the product of bankfull cross-sectional area (A_{bf}) and bankfull flow velocity (V_{bf}), or as:

$$Q_{bf} = A_{bf} \times V_{bf} \qquad (4)$$

where A_{bf} and V_{bf} are calculated from Equations 7 and 3.

The wetted perimeter at bankfull flow (W_p) is determined by summing the length along the bank at bankfull flow and the width of the channel bed. The length of each line segment is calculated from the Pythagorean Theorem as:

$$L_i = \sqrt{(y_i - y_{i-1})^2 + (x_i - x_{i-1})^2}\,, \qquad (5)$$

where L_i = length of line segment i (i.e., each straight line in red in Figure 4), y_i and x_i are vertical distance (height) and horizontal distance respectively of line segment i.

The wetted perimeter at bankfull (W_{pbf}) is then calculated from:

$$W_{pbf} = \sum_{i=1}^{n} L_i. \qquad (6)$$

Since the resolution of the DEM used in this study is 1 metre, $x_i - x_{i-1}$ in Eq. 5 is also equal to 1, and the wetted perimeter in the example given in Figure 4 is composed of a total of 144 segments (i.e., n = 144).
The hydraulic radius at bankfull flow (R_{bf}) is calculated as the ratio of flow cross-sectional area at bankfull flow to wetted perimeter at bankfull flow. From the bankfull flow cross-section given in Figure 4, the area of bankfull flow (A_{bf}) can be calculated as:

$$A_{bf} = \mathrm{A_r} - \mathrm{A_{uc}}, \tag{7}$$

where:

$$\mathrm{A_r} = E_{bf} \times W_{\mathrm{bf}}, \tag{8}$$

E_{bf} and W_{bf} are elevation and top width of channel at bankfull flow. A_{uc} is the area under the curve defining the channel at bankfull flow. This can be calculated using the trapezoidal rule as:

$$A_{uc} = \frac{\Delta x}{2}\left(y_0 + y_n + 2(y_1 + y_2 + \cdots + y_{n-1})\right) = \frac{\Delta x}{2}\left[y_0 + y_n + \sum_{i=1}^{n-1} 2y_i\right], \tag{9}$$

where $\Delta x = x_i - x_{i-1}$ is resolution of the LiDAR DEM. Since the LiDAR DEM has a resolution of 1 metre, $\Delta x = 1$. Therefore, the above equation simplifies to:

$$A_{uc} = \frac{1}{2}\left[y_0 + y_n + 2\sum_{i=1}^{n-1} y_i\right]. \tag{10}$$

It is, therefore, possible to use Eq. 4 to determine bankfull discharge given W_{bf} and H_{bf} instead of bankfull flow of a user specified recurrence interval currently adopted in P2R's population of Dynamic SedNet parameters.

It should be noted that the above formulae do not include depth of flow at the time of LiDAR data acquisition, as stated earlier in this paper. For the dataset used in this study flow depth was quite low at about 2 metres. Therefore, in the calculations for Table 1, it was assumed that the flow had a rectangular cross-section with a width equal to the width of the water surface and a depth of 2 metres.

3. RESULTS AND DISCUSSION

Figure 5 depicts how hydraulic radius assuming a rectangular channel is deviating from that of a trapezoidal channel (R_{trap}) as its bottom width W_b decreases from 400 to 100 metres while the top width W_t is kept constant at 600 metres with depth (d) assumed to be 20 metres. Figure 5 clearly shows how hydraulic radius and hence flow velocity and discharge would be overestimated when a trapezoidal channel is assumed to be a rectangular one with width equal to bankfull width (W_{bf}) and bankfull height (H_{bf}) as in the P2R application of Dynamic SedNet.

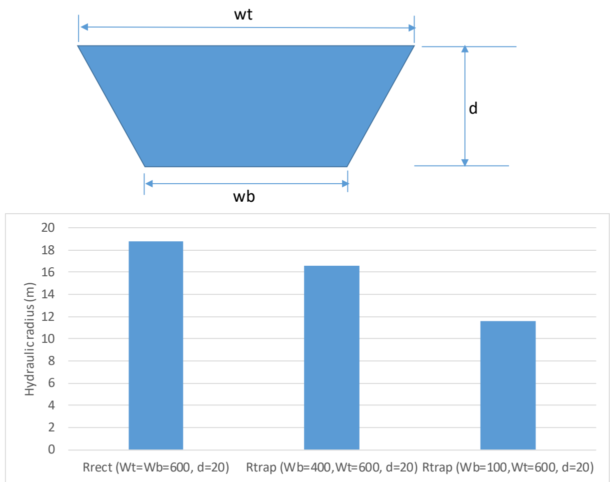

Figure 5. Top: Hypothetical trapezoidal channel cross-section; Bottom: Comparison of hydraulic radii assuming a rectangular channel against those of trapezoidal cross-section (dimensions not to scale)

Figure 6 depicts the river channel cross-sectional profile at the Miva gauging station. Channel width and height (above the water surface) at bankfull discharge as determined from the labelled coordinates on either side of the channel are 176 (i.e., 266-90) metres and 13 (i.e., 32-19) metres, respectively. Figure 7, which has been generated from the Queensland government's Water Monitoring Information Portal (https://water-monitoring.information.qld.gov.au/), shows the flow level at the Miva gauging station between 2004 and 2019. This figure shows that the average flow depth during the LiDAR acquisition period (17/07/2009 to 25/09/2009) is about 2 metres and is among the lowest during that 2004-2019 period. Therefore, adding the 2 metres water depth to the 13 metres height determined from Figure 7 gives us a bankfull height of 15 metres at this location. This is in agreement with and corresponding to the value at the point of inflection (with a discharge of about 2000 m^3/s) from the stage-discharge rating curve produced by the Queensland Government's Water Monitoring Information Portal (Binns, 2016).

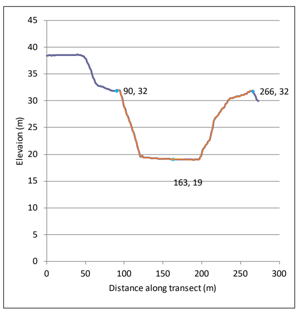

Figure 6. Cross-sectional profile at the Miva station

As outlined earlier, the profile graph data generated in ArcGIS is exported to a CSV file for generating a profile graph of stream channel cross-section at each transect. A total of 52 channel cross-section profiles have been generated (20 on SC #636, and the other 32 on SC #489). Channel dimensions and hydraulic parameters at bankfull including depth (H_{bf}), width (W_{bf}), flow cross-sectional area (A_{bf}), wetted perimeter (W_{pbf}), and hydraulic radius (R_{bf}) are calculated using equations that have been included in the Methods section.

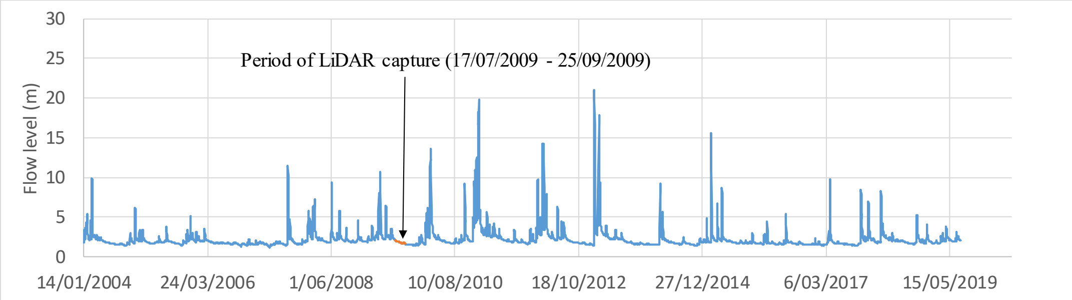

Figure 7. Historical daily flow level (m) at the Miva gauging station where the low flow depth during LiDAR data acquisition is highlighted in red

Average channel attributes at bankfull flow in the Dynamic SedNet model and corresponding values determined from the current study for each of the two modelled links are shown in Table 1. It is evident that channel attribute values in the Dynamic SedNet model are higher than the corresponding values determined from the current study. For example, the link for SC #489 has a bankfull height of 21 m in the Dynamic SedNet/Source model and only 12 as determined from this study. Given the high senstivity of the model to changes in these parmaters (e.g., according to the author's unpublished data, a 10% change in bankfull height results in about a 6% change in fine sediment export from this particular river system), it is crucial to estimate these parameters accurately. Therefore, although the Dynamic SedNet/ model has the capacity to adjust modelled erosion and floodplain deposition through calibration coefficients, overestimation of channel attributes leads to unrealistic model calibrated parameter values.

Table 1. Average values of some flow parameters at bankfull flow for two modelled subcachments estimated from this study against those applied in the current Dynamic SedNet model

	H_{bf} (m)		W_{bf} (m)		A_{bf} (m2)		Wp_{bf} (m)		R_{bf} (m)			V_{bf} (m/s)		Q_{bf} (m3/s)		
	Dynamic SedNet	LiDAR	Dynamic SedNet	LiDAR	Dynamic SedNet	LiDAR	Dynamic SedNet	LiDAR	Dynamic SedNet	LiDAR	Slope	Dynamic SedNet	LiDAR	Dynamic SedNet	LiDAR	Smanning
SC #636	21	13	207	147	4346	1457	249	153	17	10	0.000664	43	29	3232	42142	188412
SC #489	21	12	208	120	4378	2156	250	217	18	10	0.000487	37	26	3094	55071	163020

It can be seen from Figure 7 that, with the exception of one case, each of the 52 hydraulic radii determined assuming irregular channel geometry in this study is less than the corresponding value determined assuming rectangular channel geometry. Therefore, hydraulic radius and hence stream power calculated using broad data inputs and regional relationships as a function of contributing area are typically overestimated as the result of overestimations in W_{bf} and H_{bf} (Table 1), and further compounded by the assumption of rectangular river channel geometry in these models as shown in Figure 8.

4. CONCLUSION

Streambank retreat rate (RR) and floodplain deposition of fine sediment (FDfs) are two model components in Dynamic SedNet that require bankfull flow as input. A method for deriving river channel dimensions and associated hydraulic parameters from LiDAR water surface levels and flow level at the time of data acquisition is developed and applied in the Mary catchment. The method allows visual estimation of bankfull height and width followed by calculation of other bankfull hydraulic parameters such as flow cross-sectional area (A_{bf}), wetted perimeter (Wp_{bf}), hydraulic radius (R_{bf}) as well as bankfull discharge (Q_{bf}) and ultimately modelling streambank erosion.

B. Fentie, Estimating bankfull channel geometry, dimensions and associated hydraulic attributes using high resolution DEM generated from LiDAR data

The study has:

1. demonstrated that river channel dimensions and associated hydraulic attributes are more reliably determined from the use of LiDAR DEMs than by the approach typically adopted to inform catchment scale streambank erosion models (e.g., application of Dynamic SedNet in P2R),
2. shown that the assumption of rectangular river channel geometry in the P2R application of Dynamic SedNet is overestimating bankfull flow and associated hydraulic attributes such as hydraulic radius and bankfull flow in the case study reaches, and
3. demonstrated that, where it is available, application of LiDAR DEM may be a more reliable alternative to the application of the concept of recurrence interval in estimating bankfull flow.

In summary, this analysis has shown that, where LiDAR data is available, alternative approaches to determining critical bank erosion parameters could be combined with existing knowledge of river systems to better inform broad scale water quality models.

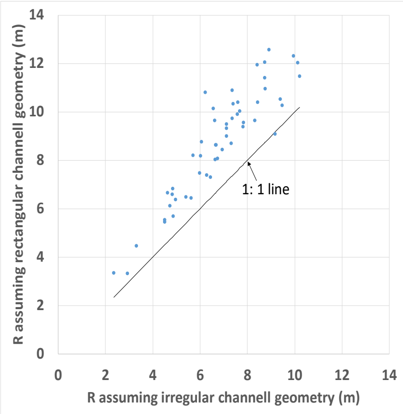

Figure 8. Hydraulic radius (R) assuming irregular channel geometry vs that assuming rectangular channel geometry

ACKNOWLEDGEMENTS

I acknowledge that the LiDAR DEM used in this paper was provided by Peter Binns (formerly of the Department of Natural Resources, Mines and Energy) who has also given feedback on potential limitations of the data for the current study, which have been listed in the paper.

REFERENCES

Bicknell, B.R., Imhoff, J.C., Kittle, J.L., Jobes, T.H., and Donigian, A.S. (2001). Hydrological Simulation Program-Fortran: HSPF Version 12 Users Manual. U.S. Environmental Protection Agency, Athens, Georgia.

Binns, P. (2016). Chronosequence mapping of streambank erosion: Mary River – Wide Bay Creek to Munna Creek. State of Queensland

Binns, P. (2017). Use of remote imagery to verify modelled streambank retreat rates. MODIM2017, Hobart, Australia, 1906-1912s

Ellis, R.J. & Searle, R.D. (2014). '*Dynamic SedNet Component Model Reference Guide: Concepts and algorithms used in Source Catchments customisation plugin for Great Barrier Reef catchment modelling*'. Queensland Department of Science, Information Technology, Innovation and the Arts, Bundaberg, Qld.

Fisher, G. B., Bookhagen, B., Amos, C. B. (2013). Channel planform geometry and slopes from freely available high-spatial resolution imagery and DEM fusion: Implications for channel width scaling, erosion proxies, and fluvial signatures in tectonically active landscapes

Hec-GeoRAS (US Army Corp of Engineers). https://www.hec.usace.army.mil/software/hec-georas/

Legleiter, C. J. (2012). Remote measurement of river morphology via fusion of LiDAR topography and spectrally based bathymetry. Earth Surf. Process. Landforms 37, 499–518

McKean, J., Nagel, D., Tonina, D., Bailey, P., Wright, C.W., Bohn, C., Nayegandhi, A. (2009). Remote sensing of channels and riparian zones with a narrow-beam aquatic-terrestrial lidar. Remote Sensing, 1, 1065-1096

Narasimhan, B., Allen, P.M., Coffman, S.V., Arnold, J.G. and Srinivasan, R. (2017). Development and Testing of a Physically Based Model of Streambank Erosion for Coupling with a Basin-Scale Hydrologic Model SWAT. Journal of the American Water Resources Association (JAWRA) 53(2):344-364. DOI: 10.1111/1752-1688.12505

Roux, C., Alber, A., Bertrand, M., Vaudor, L., Piégay, H. (2015), "FluvialCorridor": A new ArcGIS toolbox package for multiscale riverscape exploration. Geomorphology 242, 29–37

Schumann, G., Matgen P., Cutler, M.E.J., Black, A., Hoffmann, L., Pfister, L. (2008). Comparison of remotely sensed water stages from LiDAR, topographic contours and SRTM. ISPRS Journal of Photogrammetry & Remote Sensing 63 (2008) 283–296

Smart, G.M., Bind J. Duncan, M.J. (2009). River bathymetry from conventional LiDAR using water surface returns. 18th World IMACS / MODSIM Congress, Cairns, Australia 13-17

Wilkinson, S.N., C. Dougall, A.E. Kinsey-Henderson, R.D. Searle, R.J. Ellis, and R. Bartley, 2013. Development of a Time-Stepping Sediment Budget Model for Assessing Land Use Impacts in Large River Basins. Science of the Total Environment 468–469:1210-1224, DOI: 10.1016/j.scitoenv.2013.07.049.