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Modernising reach-scale stream bank erosion estimation in Australia

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Abstract: Stream bank erosion can be a significant contribution to fine sediment pollution of streams (20–80%). Australian landscape modelling approaches for quantifying the contribution of bank erosion have been dominated by the application of the SedNet mean annual stream bank erosion algorithm. This approach has served well, however the method is usually applied with limited spatial variability in representing channel dimensions or bank full flow frequency. We apply an updated version of the SedNet approach with reach-scale parameterisation of channel dimensions and bank full flow estimation derived from remotely sensed data, derived data layers and empirical relationships. To test the modernised version, we have compared the results with Queensland Government modelling results for the Fitzroy River catchment. The Queensland Government modelling for the Fitzroy catchment includes manual regionalisation of channel characteristics and bank full flow recurrence interval. The modernised approach provides an estimate of stream bank total sediment (fine + coarse sediment) approximately 1.47 times that of the government modelling approach. The modernised approach includes a finer scale stream network representation with approximately 1.5 times the stream length. The net result is a very similar overall erosion per stream length between the 2 modelling approaches. This method improves confidence in and enhances the spatial resolution of stream bank erosion estimation across Australia.

Keywords: *SedNet, Stream bank erosion*

1. INTRODUCTION

Estimating the contribution of stream bank erosion sources to both suspended and bedload sediment fluxes is an important consideration for many land and water resource managers (Castro-Bolinga and Fox 2018). In Australia the SedNet model (Prosser *et al*. 2001; Wilkinson *et al*. 2006) has been frequently adopted for reach-scale bank erosion estimation, most obviously applied to the Great Barrier Reef catchments as part of the Paddock To Reef Integrated Monitoring, Modelling and Reporting Program (P2R Program). Objective analysis of many criticisms of the SedNet bank erosion model indicates that there can be an imbalance between the scale of model interpretation and the data/parameters supporting the model (Ivezich *et al*. 2021). Indeed, the fundamental characteristics of channel geometries and representative erosional flow rates are the most tangible parameters that can be easily assessed and deemed non-representative when compared to localised observed data. With better availability of catchment delineation and climate data, we have modernised the analyses of Prosser *et al*. (2001), Tennakoon and Marsh (2007), and Dingman and Sharma (1997) to provide a consistent method of parameter estimation that can improve confidence in predictions. This modernisation combines bank full flow (Q_{bf} calculated with respect to apparent channel geometries) with mean annual flow (*MAF*) and likely erosion inducing flow recurrence, allowing for the consistent estimation of reach-scale mean annual stream bank erosion rates across Australia. By calculating erosional flow rates with respect to channel geometries (either observed or through prediction methods we describe) we also investigate the relationship between frequency of Q_{bf} (as applied in the SedNet stream bank erosion algorithm) and the calculated mean annual bank erosion rate.

By demonstrating the application of our modernised approach to estimating reach-scale mean annual stream bank erosion rates for the Fitzroy River catchment (Queensland, Australia), we have identified available data which can be used to account for other important components of the SedNet concept: the distribution and impact of intact riparian vegetation, the likelihood of erodible soil material, and elevation (for slope determination). Further application of the modernised SedNet stream bank erosion model for localised use is reasonable where fine scale data such as directly measured channel dimensions are available. However, the modernised reach-scale SedNet stream bank erosion model approach presented here is unsuitable for quantifying erosion from individual sites known to experience tidal erosion or site-specific scours/failures.

2. METHODS

The SedNet mean annual stream bank erosion algorithm (Prosser *et al*. 2001; Wilkinson *et al*. 2006) applies 'bank full discharge' (Q_{bf}) to an available sediment mass (determined by geometric estimation of height, length and density). Prosser *et al*. (2001) identified that it was common to use the mean annual flood as an estimator of Q_{bf} for stream bank erosion estimation, and that the mean annual flood discharge is typically representative of a flow rate with an average recurrence interval (ARI) of 1.58 years ($Q_{1.58}$). This indicates that stream bank erosion is assumed to be episodic and approximately annual in frequency. This also means that the magnitude of typical parameter values/ranges providing mean annual bank erosion rates (MABE) for a reach, are inherently assumed to be representative of an annual frequency. However, Prosser *et al*. (2001) also refers to observations of Australian rivers exhibiting physical characteristics (incision and widening) that are indicative of bank full discharge rates markedly higher than the mean annual flood. If an increase in Q_{bf} magnitude is applied to the estimation of MABE from the SedNet algorithm, it is reasonable to use the ARI of the Q_{bf} parameter to ensure that the SedNet algorithm provides an annualised estimate of stream bank erosion. The annualised adjustment of the SedNet stream bank erosion estimate when Q_{bf} is not representative of the mean annual flood ($Q_{1.58}$) is a significant adaptation to the SedNet concept that helps to align predictions with physically observable stream geometries.

To provide the necessary parameters for reach-scale of ARI-adjusted MABE using the SedNet algorithm we need to calculate:

- Mean annual flow (*MAF*)
- Channel geometries (channel width and height)
- Bank full discharge (Q_{bf}) associated with the observed/estimated channel geometries
- Average recurrence interval (ARI) of Q_{bf}

2.1. Mean Annual Flow

Prosser *et al*. (2001) introduced an Australian model for predicting mean annual flow (*MAF*, ML) using upstream catchment area (*A*, square kilometres) and mean annual rainfall 1950-2019 (*R*, mm):

$$log_{10}MAF = k + m\, log_{10}A + \; n\, log_{10}R \tag{1}$$

Using the HydroBASINS product from HydroSHEDS V1, mean annual rainfall from SILO, and 617 gauged flow records from Kennard *et al*. (2009), we have updated regional parameters for prediction of mean annual flow (*MAF*). There were 830 gauges with data in the Kennard *et al*. (2009) dataset, from which we selected those records where the upstream contributing area from both data sources were comparable. The updated parameters are given in Table 1, with visual representation of predicted vs observed in Figure 1:

Table 1. Revised regional Prosser *et al.* (2001) MAF prediction parameters

Region	*m*	*n*	*k*	r^2
Region 1 (Most basins)	0.996055	2.765189	-6.024	0.8629
Region 2 (Tasmania)	0.996055	2.765189	-5.787	0.9129
Region 3 (Darling River)	0.996055	2.765189	-6.160	0.8414

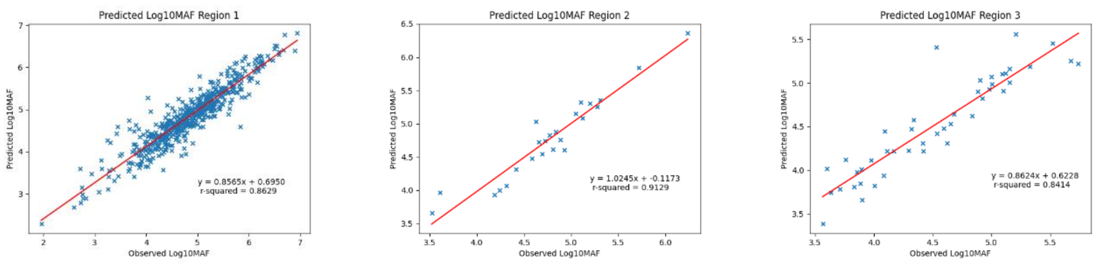

Figure 1. Predicted vs observed log_{10}MAF (mean annual flow) using revised Prosser *et al.* (2001) relationship with upstream contributing area and average annual rainfall for the three regions listed in table 1.

2.2. Channel Geometries

Downstream hydraulic geometry recognises that channel geomorphological characteristics (width, depth, slope) vary with catchment area or discharge (Stewardson *et al.* 2005). A study by Tennakoon and Marsh (2007) for Queensland rivers developed hydraulic geometry relationships for channel depth and bank top width (both related to 'channel top', defined by points of transition from the floodplain to the stream channel) similar to Stewardson *et al.* (2005), using upstream catchment area (A, km^2) $y = g * A^h$:

Table 2. Parameters used to estimate channel geometries from upstream contributing area

y	*g*	*h*	r^2
Bank top width (m)	6.8	0.27	0.25
Bank height (m)	1.36	0.19	0.20

The estimated channel geometries can be used to provide the geometry parameters for estimation of Q_{bf} using physical channel characteristics, deriving cross-sectional area (A_{bf}) and hydraulic radius (R_{bf}) as per the trapezoidal cross section calculations summarised in chapter 6 of Carey *et al.* (2015).

2.3. Bank Full Discharge

Dingman and Sharma (1997) developed an empirical model for estimating discharge (m^3/s) without the need to estimate a Mannings n value, using bank full cross-sectional area (A_{bf}, m), bank full hydraulic radius (R_{bf}, m), and slope (S, m/m). It is worth noting that R_{bf} is typically calculated from A_{bf} and bank full wetted perimeter (P_{bf}, m). The method was derived by generating an empirical relationship across 520 natural streams (r^2 0.95):

$$Q_{bf} = 1.564 * {A_{bf}}^{1.173} * {R_{bf}}^{0.4} * S^{-0.0543 * log_{10}S} \quad (2)$$

With stream slope S estimated from either local measurement or remote estimation, the Dingman and Sharma (1997) algorithm can provide a consistent estimation of bank full discharge (Q_{bf}) related to the physical characteristics of each river reach, rather than assuming the mean annual flood (or $Q_{1.58}$) is representative of the 'stream power' associated with channel incision and widening.

2.4. Mean Annual Bank Erosion Rate

The SedNet stream bank erosion rate algorithm, calculating mean annual bank erosion rate (*MABE*, t/y) is presented in Ellis (2018) as:

$$MABE = RR * MC * BE \quad (3)$$

Where *RR* is Retreat Rate (m/y), *MC* is Mass Conversion and *BE* is Bank Erodibility. Retreat Rate (*RR*) is presented in Ellis (2018) as:

$$RR = bec * p_w * g * S * Q_{bf} \quad (4)$$

Where *bec* is the bank erosion coefficient (default 0.00004), p_w is the density of water (1000 kg/m^3), g is acceleration due to gravity (9.81 m/s^2), S is the stream slope (m/m) and Q_{bf} is the bank full discharge (expressed as m^3/s, not ML/d).

2.5. Average Recurrence Interval

As Prosser *et al.* (2001) describes, Q_{bf} for stream bank erosion estimation has almost universally adopted flow rates equating to an average recurrence interval (ARI) of 1.58 years, despite observations that channel characteristics in many Australian rivers would indicate an associated Q_{bf} of higher magnitude. We propose that the annual retreat rate of the SedNet mean bank erosion rate calculation (Ellis 2018) be modified by the ARI associated with the Q_{bf} (ARI_{Qbf}) estimated by the Dingman and Sharma (1997) method, where a Flow Adjustment Factor (F_{adj}) is defined as:

$$F_{adj} = 1/ARI_{Qbf} \quad (5)$$

The term 'ARI' is not used in the SedNet stream bank erosion algorithm, we therefore use F_{adj} to modify the flow term, hence the naming of this 'Flow Adjustment Factor'. With F_{adj} applied as a proportion, it can be considered unitless. To estimate ARI_{Qbf} we have applied the techniques of Ball *et al.* (2019) to the 830 gauges of Kennard *et al.* (2009) to predict flow for recurrence intervals (Q_{ARI}, ML/d) of 1 to 10 years, and also 15, 20 and 25 years where the flow record permitted. Using least squares optimisation, the predictive Q_{ARI} algorithm was calculated as ($r^2 = 0.8$), with the prediction displayed in figure 2:

$$log_{10}Q_{ARI} = \left(ARI_{Qbf}{}^{0.06}/1.33\right) * \; log_{10}MAF \tag{6}$$

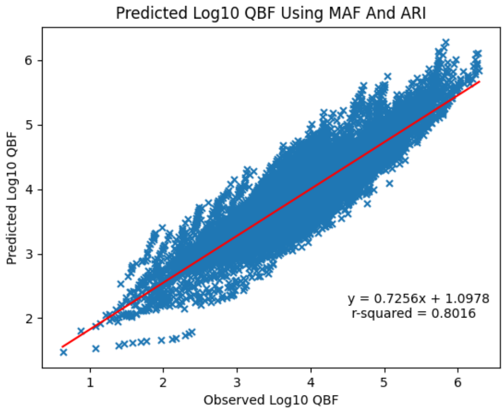

Figure 2. Predicted vs observed $log_{10}Q_{bf}$ (bank full discharge, ML/d) using mean annual flow (*MAF*, ML) and average recurrence interval of Q_{bf}.

Restructuring equation 6, we can estimate the average recurrence interval (ARI_{Qbf}) where *MAF* (ML) is known and Q_{ARI} is equal to the estimated Q_{bf} (Dingman and Sharma (1997) method, ML/d):

$$ARI_{Qbf} = \left(1.33 * \left(log_{10}Q_{bf}/log_{10}\, MAF\right)\right)^{1/0.06} \tag{7}$$

To calculate an ARI-adjusted Retreat Rate (and ultimately ARI-adjusted *MABE*) where Q_{bf} has been derived from physical channel properties, not $Q_{1.58}$, we introduce the Flow Adjustment Factor (F_{adj}) to modify equation 4. The magnitude of *RR* is now explicitly an annualised erosion rate, essential to allow for appropriate calculation of *MABE*:

$$RR = F_{adj} * bec * \; p_w * g * S * Q_{bf} \tag{8}$$

As presented in Ellis (2018), the calculation of Mass Conversion and Bank Erodibility remain unchanged:

$$MC = \; P_s * h * L \tag{9}$$

$$BE = (1 - RipVeg) * SoilErod \tag{10}$$

Where P_s is sediment dry bulk density (t/m^3), *h* is channel height (m), *L* is reach length (m), *RipVeg* is the proportion of stream banks protected by intact riparian vegetation, and *SoilErod* is the proportion of stream banks comprised of erodible sediment material.

2.6. Estimating MABE in the Fitzroy River Catchment

The Fitzroy River is a major contributor of fine sediment and particulate nutrients to the Great Barrier Reef (GBR) (McCloskey *et al*. 2021). The Fitzroy River catchment (internally broken into 7 sub-catchments for P2R Program reporting) and its smaller neighbouring catchments (Styx River, Shoalwater, Waterpark Creek, Calliope River and Boyne River) occupy an area of almost 40% of the combined GBR catchments, and together the 12 sub-catchments of the Fitzroy Region are thought to contribute almost 20% of the fine sediment delivered to the GBR lagoon (McCloskey *et al*. 2021). Approximately half of the fine sediment delivered from the Fitzroy River has been attributed to stream bank erosion sources (McCloskey *et al*. 2021). Figure 3 shows the 12 sub-catchments of the Fitzroy Region.

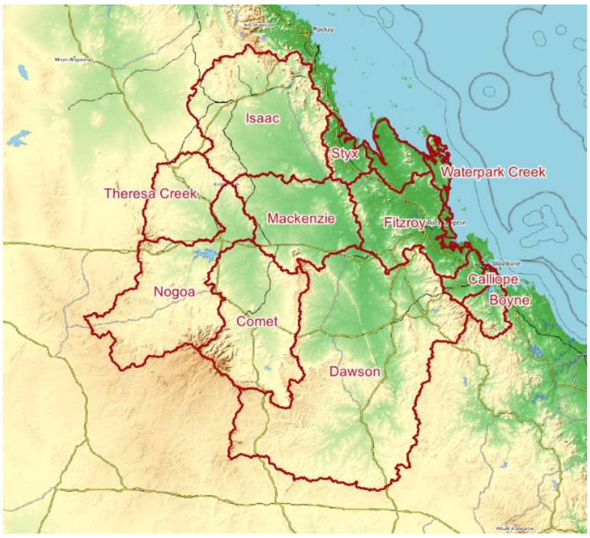

Figure 3. Fitzroy Region sub-catchments for reporting and aggregation

2.6.1. Existing MABE Estimates for the Fitzroy River Catchment

Using the SedNet-style modelling prediction of McCloskey *et al.* (2021) it is possible to calculate the mean annual bank erosion rates for all of the reaches within the 12 Fitzroy sub-catchments and aggregate these. Interrogating the individual reach parameters utilised by McCloskey *et al.* (2021) it is evident that the MABE values predicted by their models used a bank erosion coefficient (*bec*) of just 0.000002, with Q_{bf} derived from modelled flows using a range of ARI values, mostly between 5 and 10 years (although the complete range is 3 to 25 years). McCloskey *et al.* (2021) did not use the ARI-adjusted methods that we are investigating in this analysis.

2.6.2. Channel Geometries, Bank Full Discharge and ARI Adjustment Factor

To assess the validity of our proposed ARI-adjusted *MABE* method, we have calculated *MABE* for all of the HydroRIVERS stream features (from the from HydroSHEDS V1 data). Mean annual flow was calculated using the revised Prosser *et al.* (2001) algorithm with inputs from HydroBASINS (HydroSHEDS V1) and SILO. Bank top width and bank height were estimated according to the Tennakoon and Marsh (2007) relationships, with trapezoidal calculation of hydraulic parameters (toe-to-toe channel width was assumed to be one-third of bank top width). Stream slopes were estimated by determining the elevation of the start and end coordinates of each stream segment, using the Geoscience Australia service 'Digital Elevation Model (DEM) of Australia derived from SRTM with 1 Second Grid – Hydrologically Enforced'. Bank full discharge (Q_{bf}) was calculated using the derived channel geometries and SRTM-derived slopes (minimum stream slope set to 0.0001%, or 0.000001 m/m). The flow adjustment factor (F_{adj}) was calculated as per equation (5) in this document, constrained to a range of 0.02 - 1.

2.6.3. Bank Erosion Coefficient

Recognising that historic rainfall patterns have influenced the shape and characteristics of landscape and rivers, and that current rainfall influences land management and observed stream flow, it seems reasonable to provide a default Bank Erosion Coefficient (*bec*) that varies spatially with known climate patterns. Using the Bureau of Meterology's Seasonal Rainfall zones we have created 9 zones of default *bec* ranging from 0.000008 in the most arid parts of Australia, to 0.0002 in areas with extremely high summer-dominated rainfall. Most of the Australian continent is represented by *bec* values of 0.00004 to 0.00002.

2.6.4. Soil and Vegetation Parameters

The bulk density of sub-soil was determined by buffering each stream segment using a dynamic width, varying with HydroRIVERS stream order. Each buffered stream segment calculated the spatial average of the 'Soil and Landscape Grid National Soil Attribute Maps - Bulk Density - Whole Earth - Release 2', 60-100 cm layer. The same buffered stream segments features were used to determine *RipVeg*, the proportion of available stream banks protected by intact riparian vegetation (Geoscience Australia DEA Land Cover Level 4, 2020), classified to represent woody vegetation > 15% canopy cover.

To calculate *SoilErod*, the proportion of stream banks comprised of erodible sediment material, 2 data sets were combined, one representing landscape position, the other representing the degree of weathering of nearsurface materials. For landscape position consideration, Geoscience Australia's Multi-Resolution Valley Bottom Flatness (MrVBF) layer was classified into 3 erodibility factors groups as per table 4:

Table 4. Multi-Resolution Valley Bottom Flatness conversion to Soil Erodibility Factor

MrVBF Values	Description	Erodibility Factor
MrVBF <= 2	Erosional landscape	0.20
3 <= MrVBF <= 5	Valleys, likely depositional	0.70
MrVBF > 5	Extensive depositional landscape	0.95

The weathering component of soil erodibility was sourced from Geoscience Australia's 'Weathering Intensity Model of Australia'. The Weathering Intensity Model provided numeric values on a continuum from 1 to 6 representing 'Unweathered bedrock' to 'Intensely weathered' (Wilford 2012). These values were converted to a range of proportional values (0.01-1) representing erodibility factor. The landscape (MrVBF) and weathering erodibility factors were combined through multiplication to provide a single *SoilErod* layer for buffered stream segment characterisation.

2.6.5. Comparing MABE Estimates For the Fitzroy River Catchment

With the modernised SedNet *MABE* estimates calculated for every HydroRIVERS stream segment in the Fitzroy Region, the *MABE* values for each stream segment were aggregated to compare to the aggregated *MABE* estimates of McCloskey *et al*. (2021). Figure 4 shows the comparison of the aggregated *MABE* estimates.

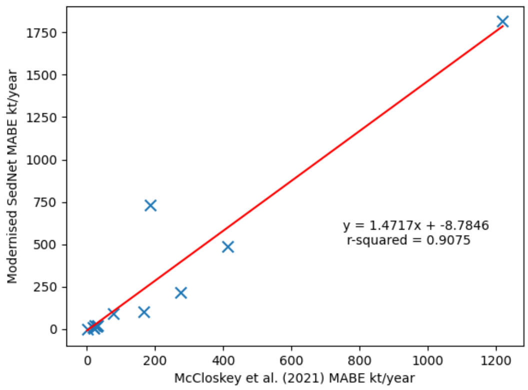

Figure 4. Regionally aggregated MABE rates (kt/y) for the Fitzroy Region, comparing modernised SedNet estimates to McCloskey *et al.* (2021

The modernised SedNet algorithm, including ARI-adjustment, has provided regionally aggregated *MABE* totals approximately 1.47 times greater than the work of McCloskey *et al*. (2021), with aggregated stream length also greater by about the same magnitude (1.51 times greater, r^2=0.99). This indicates that our relatively unsupervised application of the modernised SedNet *MABE* analysis, using only broad scale data and no localised parameter constraints, provides *MABE* per stream length rates approximately equal to those achieved by McCloskey *et al*. (2021). Performance of *MABE* prediction at individual reach/stream scale has not been conducted for this analysis.

3. DISCUSSION AND CONCLUSION

Using the HydroRIVERS representation of river features to characterise an area as large as the Fitzroy River catchment is convenient, but not without limitations. In many cases the coarse construction of the features (and limited vertices) does not accurately represent the obvious river pathway, especially in meandering locations. This will cause the length of the 'real' stream feature to be under-estimated. Additionally, the coarse construction of the HydroRIVERS stream features means that retrieving a representative elevation value for the start and end points of each feature is susceptible to poor locational accuracy. The two issues associated with the coarseness of the HydroRIVERS features can compound, providing estimated stream slopes significantly higher than expected, and sometimes lower than expected. Being aware of this allows for the use of constraints to both modelling and interpretation. As our Fitzroy River catchment example has shown, the modernised SedNet algorithm can be successfully applied with existing data for broad scale analysis, however it is not restricted to parameterisation from any single source. Improved predictions, particularly for application at local scales, could be achieved through directly measured channel characteristics, soil properties and discharge measurement.

Introducing the ARI-adjustment concept allows for the SedNet stream bank algorithm to explicitly represent the physical channel geometries that occur in Australian rivers. Whilst practitioners of the SedNet-style modelling had already begun to implicitly align model parameters with channel dimensions (McCloskey *et al.* (2021) sourced Q_{bf} from spatially varying ARI analysis of modelled flow), the explicit consideration of the frequency of Q_{bf} with respect to prediction mean annual bank erosion rates is novel.

This investigation has shown that the SedNet stream bank erosion algorithm is still relevant for reach-scale analyses supporting catchment management and planning. Identifying available broad scale data and demonstrating how to process these inputs makes the analysis of likely *MABE* rates available to more land managers and organisations responsible for whole-of-catchment management. With growing pools of data pertaining to landscapes, rivers, forests and climate, the SedNet stream bank model can contribute much to estimating current rates of sediment entering our waterways. The SedNet stream bank model continues to be useful for predicting indicative outcomes of riparian improvement activities, and could be used to assess water quality improvement through time if reliable time-stepping riparian vegetation extent data was acquired.

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