FINAL REPORT FOR QUEENSLAND WATER MODELLING NETWORK

Review of existing bank erosion prediction models, opportunities and research gaps report

Report prepared by Alluvium Consulting

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The Queensland Water Modelling Network (QWMN) is an initiative of the Queensland Government that aims to improve the state's capacity to model its surface water and groundwater resources and their quality. The QWMN is led by the Department of Environment and Science in partnership with the Department of Natural Resources, Mines and Energy and the Queensland Reconstruction Authority, with key links across industry, research and government.

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1 Introduction

1.1 Overview

Alluvium Consulting Australia Pty Ltd (Alluvium) have been engaged by the Department of Environment and Science (DES) to investigate and assess options and opportunities for stream bank erosion modelling within the Great Barrier Reef (GBR) catchments. This study will investigate a range of stream bank erosion modelling approaches and assess their applicability to GBR streams.

1.2 Project appreciation

Stream bank erosion represents a major source of sediment to the GBR lagoon. Erosion is a natural and essential process in alluvial systems; however human activities such as land clearing, removal of riparian vegetation or grazing pressure that limits reestablishment of vegetation can result in accelerated rates of stream erosion resulting in damaging channel change. These erosion processes provide a pathway for sediments and nutrients, such as nitrogen and phosphorous, to enter waterways. Land use changes within the GBR catchments have resulted in significant increase in sediment and nutrient loads to the GBR lagoon. As a result, stream bank erosion has been identified as a major sediment and particulate nutrient delivery process impacting on the GBR (Figure 1, Figure 2 & Figure 3).

Figure 1. *Stream bank erosion along the O'Connell River (left) and Mary River (right).*

The Dynamic SedNet model is currently used within the GBR Source Catchment Modelling framework to assess end of catchment loads and to estimate pollutant load reductions due to adopted improved management practices. The Dynamic SedNet is also used to run scenarios to assess efficacy of other proposed practices. The model, and the data inputs currently utilised, is a reasonable tool for estimating the relative contribution of bank erosion at large whole of catchment scales. However, its applicability at smaller spatial scales (i.e. reach or sub-catchment) to estimate erosion rates and undertake prioritisation is limited due to the coarse datasets used, size of the model links and sub-catchment areas and modelling assumptions. Recent studies have criticised the use of the Dynamic SedNet model for stream bank prediction at anything less than sub-catchment scale, and for using it as a reach-scale rehabilitation prioritisation guide (Brooks et. al. 2014).

Figure 2. *Stream bank erosion along the Mimosa Creek (Dawson River catchment) (left) and Burnett River (right).*

Significant funding is currently being invested in stream restoration within the GBR catchments. The existing Dynamic SedNet model is currently used as a tool to identify sub-catchments at risk of a stream bank erosion. Given the funding currently being invested in stream restoration, improved approaches are required to identify areas (at the reach or sub-catchment scale) where stream bank management would help reduce sediment and nutrient loads.

Figure 3. *Stream bank erosion along the Russell River (left) and Fitzroy River (right).*

1.3 Project background

The proposal for this project was developed based on the following two reasons:

- The recognition that the current form of the Dynamic SedNet model, as applied for Reef 2050 Water Quality Improvement Plan (Reef Plan) by Paddock to Reef (P2R) (often with coarse datasets), is susceptible to misrepresenting erosion rates at the reach or sub-catchment scale
- There has been extensive collection of LiDAR data in recent years across many of the GBR river systems that allow comparisons to a 2009/2010 dataset collected by the Queensland State Government which can assist in improving stream bank erosion prediction approaches

The project team is aware of LiDAR data collected in either 2018 or 2019 across significant lengths of river systems in the Mary River, Burdekin River, Fitzroy River and tributaries and streams of the Mackay Whitsundays region. Comparing these datasets to the 2009/2010 data provide an opportunity to either improve existing stream bank modelling or test alternative approaches.

This report assesses four different stream bank erosion prediction approaches. This includes:

- The Dynamic SedNet stream bank erosion model
- Bank Assessment of Non-point Source Consequence of Sediment approach (BANCS)
- The Bank Stability and Toe Erosion Model (BSTEM)

- Stream type based approach and multi-temporal analysis

For each model an overview is provided, along with examples of application, limitations and research opportunities within the context of stream bank erosion prediction in the GBR catchments.

2 Review of existing bank erosion models

2.1 Dynamic SedNet Stream Bank Erosion model

Description of the approach

Dynamic SedNet is a daily time-stepping sediment budget model which is implemented within the Source integrated modelling system. The model simulates spatial patterns in primary erosion processes at a catchment scale using data relating to terrain, land use, riparian vegetation cover, soils and rainfall. SedNet is used within GBR catchments to model sediment transport processes and the impacts of river management practices.

Dynamic SedNet is semi-distributed spatial model used to assess end of catchment loads. It is structured around river reaches (described as links) and their associated sub-catchments. Within sub-catchments the model uses Functional Units (FU) to represent different hydrological responses based on land use (Figure 5). Dynamic SedNet uses a daily rainfall-runoff model to predict runoff for each FU in each sub-catchment, and subsequently to predict daily flow and bankfull flow for each stream link (Wilkinson et al., 2014). Flow data is used in the subsequent modelling of daily fine sediment budgets for each link in the river network. SedNet is comprised of multiple models, with each component modelling a specific process (i.e. stream bank erosion, floodplain deposition etc.).

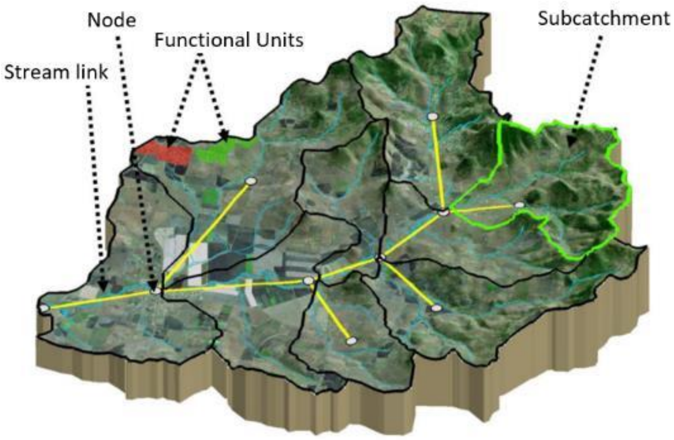

Figure 4. Example of a Dynamic *SedNet functional node and link network implemented within Source (adapted from Hateley, 2014)*

The Stream Bank Erosion component of Dynamic SedNet models bank erosion along stream links represented in the node-link (stream) network. Any channel erosion upslope of the node-link network needs to be represented by the gully erosion model. However, erosion in small tributary streams with catchment areas smaller than the threshold sub-catchment area, but larger than the gully erosion mapping, is currently not assessed (Prosser, 2018). These "missing" small ephemeral channels were identified by Brooks et al. (2013) in the Normanby catchment as potentially representing a large proportion of the catchment sediment budget. The full Dynamic SedNet Stream Fine Sediment model is a composite model which combines this Stream Bank Erosion model with the options of including floodplain deposition and/or channel deposition/remobilisation modelling as shown in Figure 5.

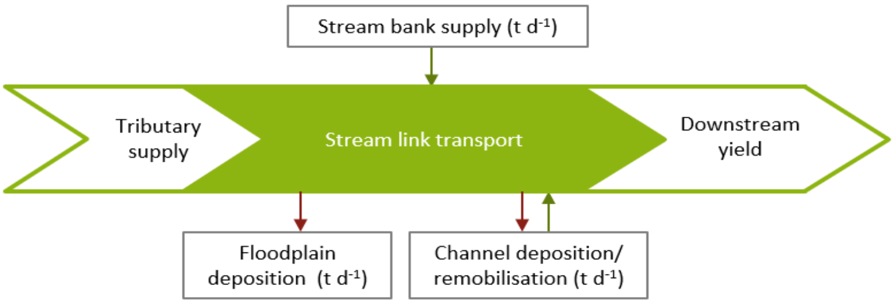

Figure 5. *Dynamic SedNet daily suspended sediment budget for each sub-catchment/stream link (adapted from (Wilkinson et al., 2009)*

The Bank Erosion component models mean annual sediment supply from bank erosion along a link as a function of bankfull stream power in a hypothetical rectangular channel, and the extent of riparian vegetation adjacent to the channel and level of bedrock confinement as represented by available geological maps (as proxies for erosion resistance) (Figure 6). The bank erosion algorithm calculates the erosion rate over the entire length of the link. The erosion rate is then scaled down based on the proportion on the reach (link) with intact riparian vegetation cover (Prosser, 2018). Mean annual bank erosion (t/y) is calculated as shown in Figure 6.

Figure 6. *Mean annual bank erosion equation*

The lateral retreat rate (RR) is the product of total bankfull stream power and calibration and management factors:

$$\mathbf{RR} = (\mathbf{k}\ \rho_{\mathbf{w}}\ \mathbf{g}\ \mathbf{S_l}\ \ \mathbf{Q_{bf}})\mathbf{M_f}$$

Where:

ρ_w = density of water (1000 g/m^3)

g = acceleration due to gravity (9.81 m/s^2)

S_l = link stream bed slope (dimensionless)

Q_{bf} = bankfull discharge (m^3/s)

k = bank erosion calibration coefficient

M_f = bank erosion management factor

The bank erosion calibration coefficient is adjusted (according to available monitoring data) to ensure long term erosion rates are comparable with observed rates. Consequently, good quality monitoring data is required to calibrate the model. Previous SedNet studies based in Australia employed K values in the range 0.00001 – 0.0001. The bank erosion management factor, introduced to allow proportional manipulation for Reef Plan, allows for adjustment of retreat rate based on proposed management actions.

Mass Conversion (MC) is determined by bank height and soil density:

$$\mathbf{MC} = \mathbf{F_b}\ \ \rho_{\mathbf{s}}\mathbf{h}\ \mathbf{L_l}$$

Where:

Fb = proportion is fines in bank materials

ρs = streambank soil dry bulk density (t/m3)

h = bank height (m) (‘bank’= erosion contributing feature)

Ll = river length represented by link (m)

Bank erodibility (BE) is considered riparian vegetation cover and bank material erodibility:

$$\mathbf{BE} = \big(\mathbf{1} - \mathbf{MIN}\ (\mathbf{RipVeg}, \mathbf{MaxVegEffectiveness})\big) \times \mathbf{SoilErod}$$

Where,

RipVeg = proportion of intact riparian vegetation

MaxVegEffectiveness = cap on the effectiveness of riparian vegetation

SoilErod = stream bank material erodibility (0 for bedrock, 1 for alluvium)

MaxVegEffectiveness acknowledges that stream bank erosion occurs in fully vegetated riparian zones.

The mean annual erosion is then converted to daily bank erosion using a disaggregation function based on daily stream flow (Figure 7). Daily stream bank erosion is calculated as shown in Figure 7.

$$\text{Daily bank erosion (kg/day)} = \frac{1}{365.25} \times \text{Mean annual bank erosion (t/y)} \times \text{Stream link discharge factor} \times 1000$$

Figure 7. *Disaggregation mean annual bank erosion to daily bank erosion*

$$\textbf{Stream link discharge factor} = \frac{Q_i^b}{\frac{1}{n}\sum_{i=1}^{n} Q_i^b}$$

Where,

Q_i = daily flow rate (m^3/s)

n = number of days in the long term historical daily flow record

b = adjustable Daily Flow Power Factor (default 1.4).

Within Dynamic SedNet, fine sediment can be transported, stored and remobilised within links based on sediment transport capacity estimates. The model also accounts for losses of fine sediment through floodplain storages which requires an understanding of the volume of floodplain flow, floodplain area and settling velocity.

Coarse sediment fraction is determined based on the percentage of fines in bank material (i.e. 1 - Fb). There is currently no coarse sediment transport accounted for within Dynamic SedNet as P2R program (and thus GBR catchment modelling) is only concerned about the transport of fine sediments to the GBR lagoon. All coarse sediment is deposited within the link (i.e the river) and no remobilisation occurs. There is no upper limit for coarse sediment deposition.

Model input parameters

Several raster data layers and parameter values are used to build the Dynamic SedNet Bank Erosion model. A Digital Elevation Model (DEM) is used to define both the sub-catchments and the stream network. To determine sub-catchment and stream networks an area threshold for first -order river link must be determined (Wilkinson et al., 2014). Often this area threshold is specified based on computational efficacy and gully erosion mapping . Input raster layers are used to calculate eight raster data sets used in parameterisation (slope, flow direction, contributing area, ephemeral streams, stream order, stream confluences with main channel and stream buffers) (Hateley et al., 2014), although some of these do not contribute directly to stream bank parameterisation. The modelling period is defined by the daily precipitation and potential evapotranspiration data available for input into the daily rainfall-runoff model. Input parameters required for the Dynamic SedNet Bank Erosion component are outlined in Table 1.

Table 1. Dynamic SedNet Bank Erosion input parameters and potential data sources

Parameter	Units	Description	Data source
k (bank erosion coefficient)	[0.00001, 0.0001]	Bank erosion calibration coefficient (default 0.00004)	Based on empirical data sets
S_l (river link slope)	m/m	Link stream bed slope	Included in SedNet plugin, based on DEM and links
Q_{bf} (bank full discharge)	m^3/s	Bank full discharge (m^3/s) based on the selected ARI (default 1.58 yrs)	Derive ARI discharge (m^3/s) based on long run of hydrology in Source model
ρ_s (soil bulk density)	tonnes/m^3	Streambank subsoil dry bulk density	http://www.clw.csiro.au/aclep/soilandlandscapegrid/ProductDetails-SoilAttributes.html
h (bank height)	m	Function of catchment area and slope	Dynamic SedNet spatial parameteriser calculates average height at link level

RipVeg	[0, 1]	Proportion of vegetation in riparian zone (1 for complete cover, 0 for no cover)	Vegetation cover mapping e.g. Queensland 2007 foliage protection cover layer. Clipped using a 100 – 200 m stream network buffer
MaxVegEffectiveness	[0, 1]	Sets limit for effectiveness of riparian vegetation in mitigating erosion	Set as 0.95 (Wilkinson et al., 2009)
SoilErod	[0, 1]	The erodibility of stream bank material (0 for rock, 1 for erodible soil). Or based on floodplain width (1 within mapped floodplain area, 0 elsewhere)	Floodplain mapping
p_f (proportion fine)	[0, 100%]	Proportion of fine sediment in bank subsoil	Best available soils data

Applicability to GBR streams and limitations

Comparative studies

The Dynamic SedNet model is currently used to simulate stream bank erosion processes in the GBR catchments. The purpose of the model is to:

- Help identify the portion of the catchment sediment and nutrients loads which are derived from stream bank erosion
- Identify areas where stream bank management would help reduce sediment and nutrient loads

To inform the Reef Plan modelling, relatively crude datasets or assumptions are used to determine link slopes, bank heights, vegetation coverage and bankfull flows. This is due to the vast scale of the GBR catchments and the relatively poor data availability inland of the coastal fringes. However the P2R modelling team do incorporate new data and expert knowledge as it becomes available, as part of a continuous model improvement venture.

There have been several studies which have assessed SedNet stream bank erosion rate estimates against observed erosion rates within the GBR catchments. Bartley et al. (2008) assessed modelled SedNet bank erosion rates against observed data in a 14 km section of the Daintree River and found the model significantly underestimated bank erosion rates. The results suggest there is a 74-fold difference between the average measured (0·74 m/yr) and modelled (0·01 m/yr) bank erosion rates. The modelled erosion rates were significantly improved when locally measured bed slopes were adopted (0.32 m/yr). Further improvements were achieved when local estimates of bankfull discharges were used (0.42 /year). This study highlights the risks of using crude estimates for bed slope derived from low resolution topographic datasets within SedNet.

Brooks et. al (2014) compared observed (LiDAR derived) mean annual bank erosion rates and SedNet predicted rates in both the upper Brisbane River and the O’Connell River. The study concluded the SedNet model had very poor predictive power in both these systems. The reach scale was altered in the O’Connell River from the modelled link lengths to one kilometre segments but this did not improve the predictive power.

More favourable modelling results have been determined recently in the O’Connell River system following a calibration process (Baheerathan et.al. 2017). Along the O’Connell River the Dynamic SedNet modelled result between 2010-2014 was comparable to the O’Connell River stability assessment (Alluvium,2014) (i.e. the modelled estimate was only 8% greater than the Alluvium (2014) estimates). Baheerathan et.al. (2017) used the Alluvium (2014) results from the upper two reaches (~ 15 km out of 45 km) to calibrate the bank erosion coefficient (k) within the model. The calibrated model was then validated on the remaining reaches. It should be noted that the modelled links, which corresponded to tributary junctions, matched the geomorphic reaches defined in the O’Connell River stability assessment (Alluvium, 2014).

Baheerathan et.al. (2017) also compared Dynamic SedNet modelled stream bank erosion along the lower Burnett River, East and West Normanby Rivers, and Laura River against published estimates. The Dynamic

SedNet modelled result along the lower Burnett River between 2009 and 2013 was approximately six times less than the Burnett River Channel and Bank Assessment (BRCBA) estimate (Cardno ENTRIX, 2014), although extrapolation of the BRCBA erosion rates were also unable to reliably match observed in-stream sediment measurements. The Dynamic SedNet and Normanby Basin Sediment Budget Assessment (NBSBA) estimates of stream bank erosion were also significantly different (Brooks et al., 2013). Dynamic SedNet modelled stream bank erosion along the East and West Normanby, and Laura Rivers were approximately 75, 50 and 55 times less than the NBSBA estimates respectively. However, this comparison did not consider the compartmental sediment budget included in Dynamic SedNet and the conceptual overlap of stream banks, stream channels and near stream gullies (as sources of sediment). This particular comparison is a good example of where reliable measurement has helped to guide improvement of the overall sediment budget at specific locations throughout the GBR catchments. Due to the very large discrepancies between the modelled estimates and published estimates no calibration attempts were made for the Burnett, Normanby, and Laura systems. Authors of Baheerathan et.al. (2017) felt that extrapolating site specific BSTEM result from one site to another may have overestimated total bank erosion by several orders of magnitude.

Binns et. al. (2017) compared the stream bank retreat rates currently implemented in Dynamic SedNet along the Mary River to rates estimated using historical aerial imagery and satellite imagery (remote imagery). At the catchment scale the estimated retreat rate estimated in Dynamic SedNet was comparable to the remote imagery estimates. However, at a finer scale (i.e. individual stream links) there were discrepancies between modelled and remote imagery estimates. Binns et. al., (2017) concluded that more accurate estimates of retreat rates may be achieved at a stream link scale by refining the stream bank erosion algorithms or the applied data values.

The above mentioned comparative studies highlight the enormous variations in predictive powers of the SedNet bank erosion algorithm. Given the limited number of comparative studies and the large variation in river typologies and data availability in these studies it is difficult to draw definitive conclusions on the suitability of the model in different scenarios (i.e. river typologies and data availability). However, these studies do indicate that improved predictive power may be achieved locally through a calibration process and the use of locally relevant slope and bankfull flow data.

River typology

Within the GBR catchments there are a huge diversity of river typologies ranging from classic self-formed meandering systems, anatomising systems, macro-channel systems which are confined by resistant floodplain/terrace material with contemporary (i.e. Holecene) inset deposits, bedrock constrained, semi-alluvial channels and typical incised channels as defined by Schumm et al (1984) (typically in smaller secondary channels). The erosional processes within the channel will differ significantly for each type of river system.

The bank erosion equation in the SedNet model was based on the empirical relationships presented in Walker and Rutherfurd (1999) and Rutherfurd (2000) that used a global meander migration dataset to derive a channel erosion rate as a surrogate for bank erosion. Leaving aside the fact that it is inappropriate to be applying global average channel migration rates to Australian rivers, it is unlikely that such a simple empirical relationship, or any empirical model for that matter, would be able to accurately predict stream bank erosion in all river typologies that exist within the GBR catchments. However, to date there has been limited work to assess the accuracy of the bank erosion algorithm used with the SedNet model in each different river typology. The model performance may be superior in certain river typologies compared to others, but this as yet has not been assessed. Currently, GBR river typologies have not been systematically described or mapped.

Stream power

Within the SedNet model bankfull stream power is considered the dominate driver of bank erosion. Brooks et. al. (2014) found either a weak inverse relationship or no relationship between stream power and stream bank erosion in the Upper Brisbane, O'Connell, and Normanby catchments. However, Prosser (2018) argues this may be due to limits to statistical analysis such as the ranges of stream power under investigation relative to its variability in time and space across large regions. Stream power is still likely to be a significant driver of channel erosion in almost all river typologies, however the high variability in the characteristics and erodibility of the channel boundary material and riparian vegetation make finding reach scale correlations between stream power and channel erosion problematic. This variability in erodibility is currently poorly parameterised within Dynamic SedNet as applied in Reef Plan models using GBR-wide available data.

Two of the primary input variables for stream power estimation are bankfull discharge and channel slope. Bankfull discharge (and hence stream power) is determined based on calculating average recurrence interval discharges. These are often based on an empirical relationship developed from global rivers with active floodplains. However, evidence suggests that the macro channel morphology of Queensland rivers allows for the confinement of much higher discharges. There are also issues with estimating low gradient river slopes from low resolution DEMs. Large variations in erosion rates have been predicted using locally derived bed slopes compared to bed slopes derived from low resolution DEMs (Bartley et al. 2008).

Prosser (2018) made several recommendations relating to the assessment of stream power within the SedNet stream bank algorithm. These include:

1. A better understanding of the magnitude and frequency of bankfull flow in different river typologies
2. A better understanding of the relationships between stream power and erosion rate at the broadest spatial scales for different river typologies
3. Investigate the applicability of other stream power metrics including cumulative stream power, mean specific stream power and threshold stream power below which no work is done on the channel
4. Investigate methods for improving channel slope determination in the stream power calculations

These recommendations, along with improved parameterisation of erodibility, could improve the application of SedNet to stream bank erosion prediction.

Erodibility

The Dynamic SedNet model assumes uniform sediment and vegetation characteristics across the link length. SedNet assumes that all alluvium has an equal erodibility unless it is bedrock. However, variations in channel erodibility relative to stream power can be adjusted through the bank erosion coefficient when monitoring data is available.

Many rivers in the GBR catchments, have a compound channel morphology with several depositional units within a broader macrochannel bounded by resistant terraces/floodplains. Each of these can have a different sediment composition and erodibility at the cross-section scale. At the reach scale, Brooks et.al., (2014) found the variability in the character and erodibility of in-channel boundary sediments overwhelms other controls (i.e. stream power).

In GBR streams there are often large variations in erodibility both longitudinally along the reach and laterally within the strata of floodplains and other depositional units. Alluvial channel boundary erodibility can vary by several orders of magnitude. As a result, it is very problematic to make uniform assumptions of sediment erodibility across large spatial areas. This issue is likely to be a limiting factor in most stream bank erosion models which adopt uniform assumptions of sediment erodibility.

Summary and research opportunities

Despite criticisms in the application of Dynamic SedNet for stream bank erosion prediction in Reef Plan models, it remains the primary mechanism for predicting stream bank erosion within the GBR catchments. The outputs of these programs are then used to prioritise management interventions for stream bank management.

In the limited comparative studies identified in this review calibration and the use of locally relevant data can improve model prediction. However, in the vast majority of streams within the GBR catchments this information is not available. As a result, for the majority of reaches in the GBR catchments we have relatively low confidence in the stream bank erosion predictions.

This review and the outcomes of the recent Prosser (2018) review have identified several areas where research could improve the application of Dynamic SedNet for stream bank erosion prediction. These include:

- An assessment of the applicability of the model to the varying river typologies that exist within the Great Barrier Reef catchments
- Research into the application of the stream power parameter including alternative metrics, parameterization and application in different river typologies
- A thorough assessment of bank material erodibility and the development of empirical erodibility datasets within different geomorphic units
- A framework to assist in developing confidence bands on stream bank erosion prediction results based on the river typology and data availability

2.2 Bank Assessment of Non-point Source Consequence of Sediment

Description of the approach

The Bank Assessment of Non-point Source Consequence of Sediment (BANCS) approach is an empirical, process integrated model used to predict the rate and volume of stream bank erosion along river reaches in a specific hydrophysiographic region. BANCS is a reach-scale, rather than catchment-scale, bank erosion prediction model. However, the model can be used to predict erosion rates across a catchment for similar stream systems. The model integrates two bank erodibility estimation tools: the Bank Erosion Hazard Index (BEHI) and the Near Bank Stress (NBS) (Bigham et al., 2018). The BEHI and NBS data is then used to develop a relationship with annual bank erosion rate. Both indices (BEHI and NBS) are traditionally derived from field measurements although recent advancements in remote sensing data could replace some of the field assessments.

To develop a calibrated BANCS model requires the following steps (see Figure 8):

1. Estimate BEHI and NBS at a number of representative stream bank sites within a region.
2. Determine annual retreat rates for each representative stream bank site based on monitoring or multi-temporal analysis.
3. Develop empirical relationship between BEHI, NBS and annual retreat.
4. Develop predictive curve for the region. For each BEHI category, exponential regression equations are created to relate NBS with measured annual bank erosion rate.

Once developed, the predictive curves are then used to estimate annual retreat rates at the reach scale based on estimates of BEHI and NBS. Annual erosion rates are estimated and multiplied by bank height and corresponding reach bank length, providing an estimate of annual sediment yield (m^3/yr). This empirical relationship is site-specific.

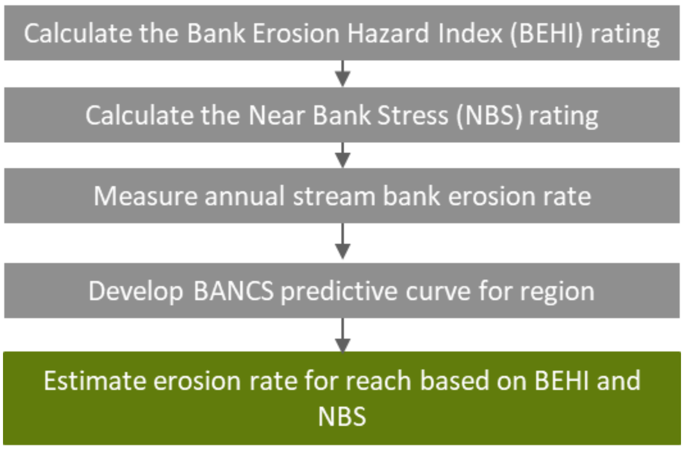

Figure 8. *The BANCS method for predicting stream bank erosion*

An example of a BANCS model calibrated for variable BEHI and NBS for the hydrophysiographic region of Yellowstone National Park, Wyoming, is shown in Figure 9. The number of study sites, data collection period, and erosion rate method utilised for model development in previous applications of the BANCS model is summarised in Table 2, but typically involved measuring bank profiles for one year at a number of sites within a hydrophysiographic region.

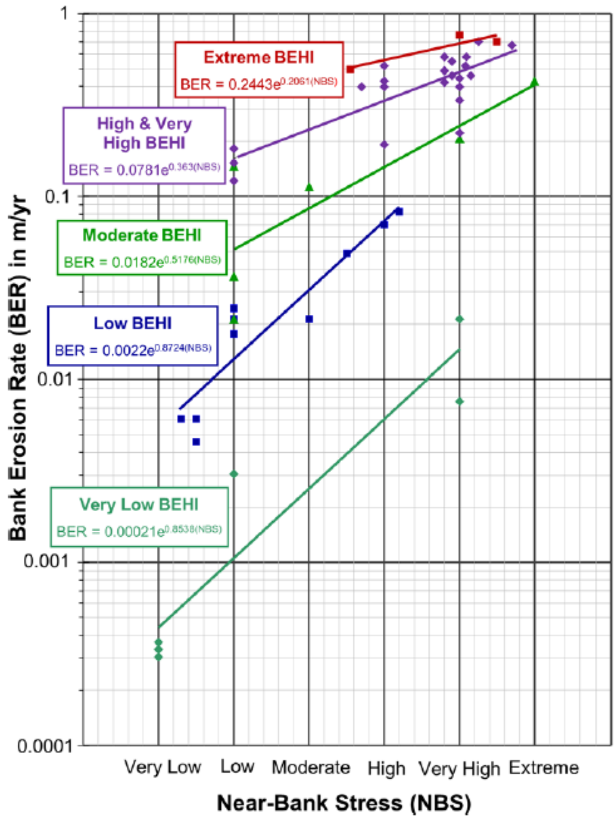

Figure 9. *Example of annual stream bank erosion prediction curves for Yellowstone National Park, Wyoming showing relationship between NBS and annual Bank Erosion Rate (BER) for various BEHI categories (from Rosgen 2009).*

Table 2. Comparison of methods and factors utilised in eight published annual stream bank erosion rate prediction curves developed from BANCS model methodology (adapted from Bigham et. al., 2018)

BANCS Model	# of sites (avg. # per regression line)[1]	Years of data	Stream flows experienced	Erosion rate method	Model fit
Colorado (Rosgen, 1996, 2001, 2009)	49 (12.3)	1	60–70% below bankfull	Bank profiles	R^2 = 0.92
Wyoming (Rosgen, 1996, 2001, 2009)	40 (8)	1	60–70% below bankfull	Bank profiles	R^2 = 0.84
Kansas (Sass and Keane, 2012)	16 (8)	4	At bankfull to 2.59 greater than bankfull	Bank profiles	R^2 = 0.75–0.77 (premodification)
California (Kwan and Swanson, 2014)	137 (34.3)	1	65% below bankfull to 1.59 greater than bankfull	Bank profiles	R^2 = 0.37–0.77
Alabama and Florida (McMillan et al., 2017)	74 (14.8)	2	Bankfull exceeded	Bank profiles	R^2 = 0.01–0.92 (premodification)
Arkansas (Van Eps et al., 2004)	24 (4.8)	1	1.39 greater than bankfull	Bank profiles	R^2 not reported
North Carolina (Patterson et al., 1999; Jennings and Harman, 2001)	31 (6.2)	1	Not reported	Bank profiles, bank pins	R^2 = 0.05–0.17 R^2 = 0.167 (BEHI)
Oklahoma (Harmel et al., 1999)	29 (9.7)	1	4 x greater than bankfull	Bank pins	R^2 = 0.09–0.32

[1]Avg. # per regression line = # of sites ÷ # of BEHI regression lines.

Model input parameters

The BEHI allocates an overall value with respect to a bank's erodibility, or shear strength. Seven variables are used as predictors of steam bank erodibility (i.e. BEHI). Variables, input parameters and data sources for BEHI assessment are listed in Table 3. A schematic of BEHI input parameters is shown in Figure 10. The BEHI variables are converted to a risk rating (1-10) (10 being extreme risk) and then summed to determine an overall BEHI rating (Table 4). The overall BEHI rating describes bank erosion potential from very low (<9.5) to extreme (>45). The latter characterises a streambank highly susceptible to erosion.

Table 3. BEHI model input parameters and data sources

	BEHI variables	Units	Description	Data source
1.	Bank height/bankfull height ratio	-	Measurement of incision (e.g. non-incised stream generally has more access to floodplain to enable energy dissipation during large flows). The closer the ratio is to 1, the lower the risk of bank erosion as there is less incision.	-
	Bank height	m	Bank height is measured from the toe to top of bank.	Field measurement
	Bankfull height	m	Bankfull height is measured from the toe of bank to a bankfull indicator (e.g. a break in slope or change in particle size distribution).	Field measurement
2.	Root depth/bank height ratio	-	The root depth/bank height ratio estimates structural reinforcement provided by roots (limiting undercutting and cantilever failure).	-
	Root depth	m	Root depth is measured from the top of bank to the extent of the dominant roots.	Field measurement
3.	Weighted root density	%	The weighted root density is the product of the root density and the root depth/ bank height ratio.	-
	Root density	%	Root density is the proportion of the stream bank composed of roots.	Field observation
4.	Bank angle	°	Measured in degrees.	Field measurement
5.	Surface protection	%	Surface protection is the proportion of stream bank covered by vegetation, woody debris, large rocks etc.	Field observation
6.	Bank material adjustment	-	Adjust the summed BEHI score (parameters 1 to 5). If bedrock the overall BEHI = Very Low If boulder the overall BEHI = Low Otherwise subtract up to 20 points or add up to 10 points based on bank material. Cobble: subtract 10 points Silt/clay: if primarily clay subtract 20 points, otherwise no adjustment Gravel or Composite matrix: add 5-10 points (depending on % sand) Sand (add 10 points).	Field observation or soil test
7.	Stratification of bank material	-	Adjust the summed BEHI score (parameters 1 to 6) based on the presence and type of bank layers which may be susceptible to piping or entrainment (add 5-10 points).	Field observation

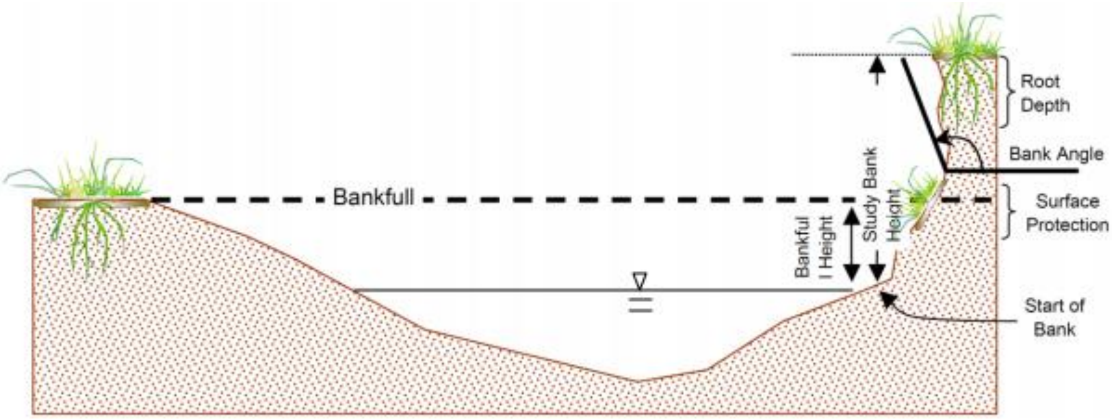

Figure 10. *Schematic of BEHI variables (from Rosgen, 2009)*

Table 4. Criteria used to convert stream bank erodibility variables to BEHI ratings (adapted from Rosgen, 2001)

Adjective hazard or Risk rating Categories		Bank Height/ Bankfull Height	Root Depth/Bank Height	Root Density (%)	Bank Angle (°)	Surface Protection (%)	Overall
Very low	Value	1.0–1.1	1.0-0.9	100-80	0–20	100–80	
	Score	1.0–1.9	1.0-1.9	1.0-1.9	1.0–1.9	1.0–1.9	5–9.5
Low	Value	1.11–1.19	0.89–0.5	79–55	21–60	79–55	
	Score	2.0–3.9	2.0–3.9	2.0–3.9	2.0–3.9	2.0–3.9	10–19. 5
Moderate	Value	1.2–1.59	0.49–0.3	54–30	61–80	54–30	
	Score	4.0–5.9	4.0–5.9	4.0–5.9	4.0–5.9	4.0–5.9	20–29.5
High	Value	1.6–2.0	0.29–0.15	29–15	81–90	29–15	
	Score	6.0–7.9	6.0–7.9	6.0–7.9	6.0–7.9	6.0–7.9	30–39.5
Very high	Value	2.1–2.8	0.14–0.05	14–5.0	91–119	14–10	
	Score	8.0–9.0	8.0–9.0	8.0–9.0	8.0–9.0	8.0–9.0	40–45
Extreme	Value	>2.8	<0.05	<5	<119	<10	
	Score	10	10	10	10	10	46–50

The NBS rating describes the relative level of shear stress acting upon the eroded stream bank due to in-stream hydraulic conditions. NBS ratings range from very low to extreme, with extreme representing the highest applied shear stress on a stream bank. NBS rating can be determined by seven different methods. Methods listed in Table 5 are ordered with increasing level of detail and resource requirement. One or more methods can be selected (based on site conditions and data availability). The highest (rather than average) rating is then applied. Required model input parameters are dependent on method selection. NBS rating ranges for methods 2 to 7 are shown in Table 6. While field measurements have traditionally been used for the various NBS assessments high resolution terrain data could also be used.

Table 5. NBS methods, model input parameters and data sources

	NBS Method	Description	Data source
1.	Presence of transverse/central bars or channel pattern changes	These features suggest stream instability and therefore, greater applied shear stress (NBS rating high, very high or extreme)	Field observation
2.	Radius of curvature/bankfull width ratio	A tighter stream bank radius of curvature to bankfull width indicates higher applied shear stress	Field measurement or aerial imagery
3.	Pool slope/average water surface slope ratio	Appropriate when stream bank is adjacent to a pool. Pool slope >40% of water surface slope indicates greater localised applied shear stress	Field measurement

4.	Pool slope/riffle slope ratio	Appropriate when stream bank is adjacent to a pool. If pool slope >60% of riffle slope, localised applied shear stress is likely	Field measurement
5.	Near-bank maximum depth/bankfull mean depth ratio	A deeper thalweg with respect to bankfull mean depth indicates great applied shear stress	Filed observation or measurement
6.	Near-bank shear stress to bankfull shear stress ratio	Near-bank shear stress $(\tau_{nb}) = \gamma d_{nb} S$ Where, γ = specific weight water, d_{nb}= near-bank maximum depth (within the 1/3 bankfull width closest to the study area), S = water surface slope Bankfull shear stress $(\tau_{bkf}) = \gamma d_{bkf} S$ Where, d_{bkf}= mean depth (bankfull area/ bankfull width)	Field measurement
7.	Velocity gradient	Based on measured vertical velocity profiles across channel (perpendicular to streambank)	Field measurement

Table 6. NBS ratings (for methods 2 to 7) (adapted from Rosgen, 2009)

NBS rating	2. Radius of curvature/ bankfull width ratio	3. Pool slope/average water surface lope ratio	4. Pool slope/riffle slope ratio	5. Near-bank maximum depth/ bankfull mean depth ratio	6. Near-bank shear stress and bankfull shear stress ratio	7. Velocity gradient
Very low	>3.00	<0.20	<1.00	<1.00	<0.80	<0.50
Low	2.21–3.00	0.20-0.40	1.00-1.50	1.00–1.50	0.80–1.05	0.50–1.00
Moderate	2.01–2.20	0.41-0.60	1.51-1.80	1.51–1.80	1.06–1.14	1.01–1.60
High	1.81–2.00	0.61-0.80	1.81-1.00	1.81–2.50	1.15–1.19	1.61–2.00
Very high	1.50–1.80	0.81-1.00	1.01-1.20	2.51–3.00	1.20–1.60	2.01–2.40
Extreme	<1.50	>1.20	>1.20	>3.00	>1.60	>2.40

Applicability to GBR streams and limitations

Comparative studies

To date there have been no comparative studies of BANCS in the GBR catchments (or Australia for that matter). However, in the USA BANCS is a widely used, empirical model, which has been approved by several key bodies in the international stream restoration community including the U.S. Environmental Protection Agency and the U.S. Forest Service (Yochum, 2016). By reviewing its application in the USA some conclusions on its applicability to GBR catchments can be drawn.

BANCS models have been developed for several hydrophysiographic regions across the USA. In Colorado Front Range and Yellowstone National Park BANCS models showed very good fit with measured stream bank erosion rates for bankfull flows (overall R^2 values of 0.92 and 0.84 respectively) (Rosgen, 2001). More recently, a BANCS model developed for Sequoia National Forest (USA) resulted in a slightly weaker, but still strong, fit with measured stream bank erosion rates (Kwan and Swanson, 2014). The BEHI/NBS curve showed strong correlation with observed erosion rates for extreme and low BEHI classes (R^2 values of 0.76 and 0.7 respectively). Correlation was slightly weaker for high/very high and moderate BEHI classes, suggesting the BANCS model may be less accurate in the colluvial valleys which dominate the Sequoia National Forest region. Previous BANCS models were evaluated in alluvial settings (e.g. Colorado and Yellowstone regions).

In Northeast Kansas, a region subject to more episodic and sporadic erosion, modifications to the BEHI were required to achieve adequate goodness of fit (Sass et. al. 2014). It was determined that bank material and woody vegetation controls were likely to play a larger role in erosion processes than other regions. The BEHI model incorporates two vegetation parameters, however, the study found that these variables may not adequately represent vegetation endemic to Northeast Kansas. Hence, the BEHI was modified according to levels of woody vegetation along stream banks with high clay content. Modification of the vegetation component of the BEHI model enabled more accurate prediction of bank erosion rates in Northeast Kansas. Rosgen (2011) suggested that bank material adjustment for soils with high clay content and high cohesion may be a more suitable modification of the BEHI rating.

BANCS regression models developed in northern Gulf of Mexico coastal plain failed to produce statistically significant correlations to measured bank erosion rates (McMillian, 2017). The measured erosion rates, over the two years study, showed the highest variability of BANCS studies to date. Rosgen (2019) argues that extreme variability in erosion rates and lack of positive correlation may be due to the averaging of erosion rates over a two-year period, the use of different data collectors for different datasets and time periods, and the incorporation of extreme flow events. BANCS was designed explicitly to predict erosion at or near bankfull discharge ($\pm$10%) and not for predicting erosion rates during flood events or drought. Complex streambank mechanics and hydraulics associated with flood events may lead to significant variation in erosion rates, thus making predictions challenging (Rosgen, 2001). If adequate data is available, Rosgen suggests it would be favourable to develop specific prediction curves for BEHI/NBS relations for bankfull, flood and dry-year derived data.

Based on the outcomes from these BANCS studies a range of potential issues are discussed below.

Flood frequency and magnitude

The streams within the GBR river catchments flow through a diverse range of climatic regions with large variations in annual rainfall and intra and interannual flow variability. Channel erosion in many of these areas is often driven by large infrequent flood events followed by periods of minimal channel adjustment. From the studies reviewed it appears the BANCS model is most applicable to streams with low flood variability where the annual maximum flow is typically close to bankfull. In regions where there is higher flood variability (i.e. McMillian, 2017, Sass et. al. 2014) model performance has been poorer.

The BANCS model was developed to predict erosion at or near bankfull discharge under the assumption that this approximates maximum annual flow. In the GBR catchments this assumption is generally not the case. As a result, different predictive curves would need to be developed for different flow condition (i.e. flood periods, drought periods etc.) if this approach were to be applied in the GBR catchments. Given the high flow variability across most areas of the GBR catchments the development of several relationships for different flow periods in each region may be problematic.

Variety of river typologies

As discussed in Section 2.1 within the GBR catchments there are a huge diversity of river typologies. To date the studies in the USA appear to have been predominately applied to the classic self-formed meandering systems. It is currently unclear whether the BANCS model would be applicable across this diversity. For example, numerous streams in the GBR catchments have a compound channel morphology where the channel is confined by resistant terrace/floodplain units (Brooks et al., 2014). Within the bounds of the terraces multiple depositional units can form including benches and inset floodplains. Most channel erosion in these systems is confined to the inset units. It would be difficult applying the BEHI index to these systems which have a compound form where the sedimentology of each inset geomorphic unit is often independent of the adjacent unit.

Soil erodibility

Brooks et al. (2014) found that the large variability in the character and erodibility of in-channel boundary alluvium overwhelms other controls within several Queensland rivers. Many streams in the GBR catchments are likely to have boundary material consisting of a mixture of silts, clays and sands with significant variation in both cohesion and erodibility. The assessment of bank erodibility within the BEHI is very subjective and limited guidance is provided on how to score the bank material adjustment factor in these systems.

Data collection and parameterisation

The BANCS approach typically requires significant field measurement. However, the advent of high resolution terrain data can be used to assess many parameters such as bank height, bank angle and stream slope. Significant field measurements/assessments will also still be required to inform assessments of root depth, bank material and stratification.

Brooks et. al. (2014) undertook extensive investigations into tree root properties within Queensland. The study found that properties of roots varied extensively from both species to species and from site to site. As a result, it would be difficult to characterise key species and extrapolate root parameters to the broader region.

Limited guidance is provided in the BANCS approach for accounting for the different cohesion and erodibility in alluvial soils. Brooks et. al. (2014) developed a method for predicting geotechnical properties from particle size distribution (PSD) (e.g. cohesion and erodibility). When particle size data was grouped into three categories (sand, silt and clay) the model demonstrated strong predictive power with significant correlation (p value = 0.05 or less) to geotechnical variables. A similar approach could be used to parametrise the BEHI within Queensland.

Summary and research opportunities

The BANCS approach is similar to the Dynamic SedNet stream bank equation in that it is an empirical, process based model that assesses factors that drive erosion (i.e. stream power or shear stress) against channel resistance (i.e. substrate, vegetation etc.). However, the BANCS approach requires significantly more local data to determine the susceptibility of the channel boundary to erosion. Furthermore, the model requires local erosion data for calibration. Given more local data is required to inform the model development the BANCS approach may significantly improve bank erosion prediction at the reach and sub-catchment scale within many areas of the GBR catchment.

There is an opportunity to test the BANCS approach in the GBR catchments to determine its applicability. This would involve investigating approaches to limit the requirement for field investigation by using remote sensing data and the use of methods similar to those developed in Brooks et. al. (2014) to assess tree root properties and bank erodibility.

The BANCS approach may demonstrate to be a superior method of erosion prediction in certain river types where locally relevant data is available when compared to the current approach. However, several limitation or areas of uncertainty which may limit the expansion of the BANCS approach to the broader GBR catchments have been identified. These include:

- The model development requires local erosion rates over a relatively short period of time (i.e. one year) to ensure erosion rates are related to the BEHI. In many coastal streams in the GBR catchments multi-temporal LiDAR analysis is available over periods of 4 -10 years. However, within Queensland's flood prone streams BEHI can change drastically over this period as vegetation is removed or reestablished over this period. For the vast majority of inland streams within the GBR catchments no local data on erosion rates is available. To overcome this significant effort would be required to collect local erosion rate data to inform model development.
- The high flow variability in many of the GBR catchments may require several different predictive curves to be developed for different flow periods (i.e. flood periods, drought periods etc.). This could significantly increase the time required to develop the model.
- The applicability of the approach to the range of river typologies within the GBR catchments including systems with a compound channel morphology.

2.3 The Bank Stability and Toe Erosion Model

Description of the approach

The Bank Stability and Toe Erosion Model (BSTEM) is a process-based model used to predict streambank retreat (Midgley et al., 2012) and volumes of sediment resulting from stream bank erosion (Simon and Collison, 2002). The model integrates two components which simulate hydraulic and geotechnical processes that influence mass failure (bank stability module) and fluvial scour (toe erosion module) in streambanks (Figure 11). Originally an Excel (Microsoft, WA) based model, BSTEM was recently incorporated into the

Hydrologic Engineering Center's River Analysis System (HEC-RAS) model.

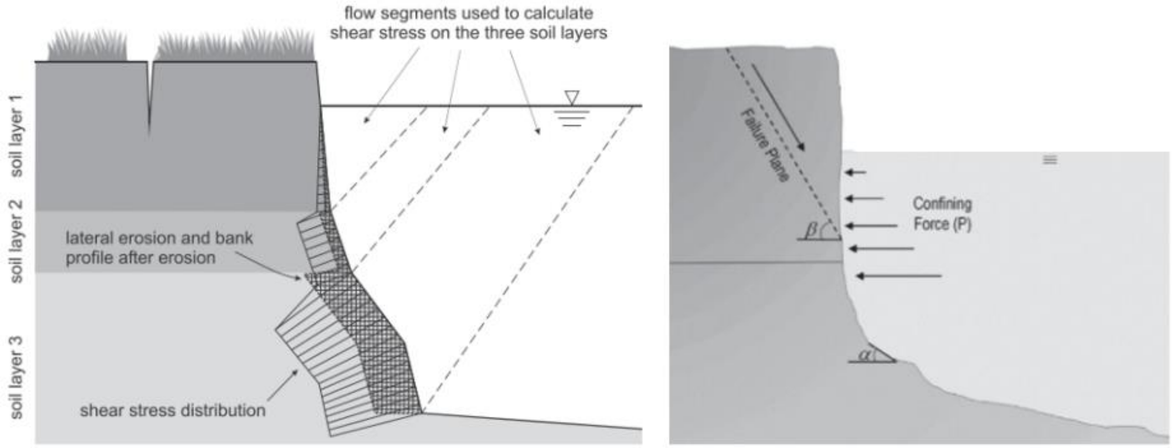

Figure 11. *Examples of segmentation and local flow areas used to calculate applied hydraulic stress (left) and forces acting on a bank during stream bank erosion and failure (Simon et al., 2009).*

BSTEM uses soil strength, erodibility and geometry data (for up to five distinct stream bank layers), stream hydraulic parameters (e.g. channel slope and manning's n), and event hydrographs to predict bank erosion. The model can predict fluvial erosion and geotechnical failure for streams which vary in geometry, bank material, vegetation cover, groundwater dynamics, and flow conditions (Simon et al., 2010). It is purpose built to test the efficacy of stream bank stabilisation treatments (both revegetation and engineered toe protection). Key components of the HEC-RAS BSTEM model are shown in Figure 12.

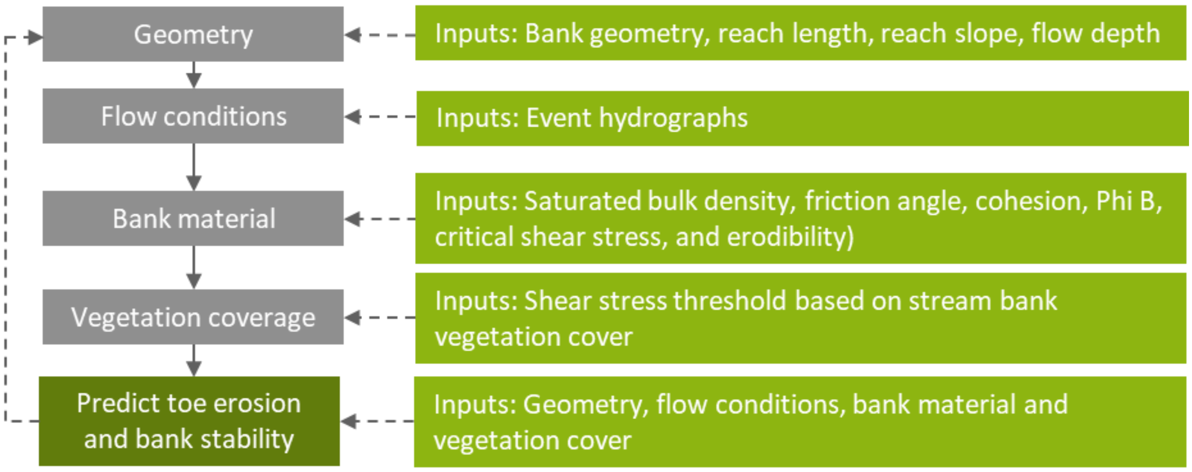

Figure 12. *Key components of the BSTEM HEC-RAS model*

The erosion component of BSTEM estimates the applied (hydraulic) shear stress along the bank toe and simulates the resultant undercutting of banks due to fluvial erosion. BSTEM predicts bank erosion based on an excess shear stress equation (Simon et al., 2000). Erosion rate ($\in_r$) is given by:

$$\in_r = \boldsymbol{k_d(\tau - \tau_C)^a}$$

Where,

k_d = coefficient of erodibility ($m^3\ N^{-1}\ s^{-1}$)

τ = average applied shear stress (kPa)

τ_C = the soil's critical shear stress (kPa)

a = an exponent usually assumed to be unity

The model uses an analytical method to estimate the applied shear stress (acting on each 'node' of bank material) based on cross-section geometry, stage, and channel slope (assuming steady uniform flow) (Figure 11)(Daly et al., 2015). Applied shear stress (τ) is given by:

$$\boldsymbol{\tau = \gamma R_h S}$$

Where,

γ = specific weight of water

R_h = hydraulic radius

S = energy slope (assumed as bed slope for uniform steady flow)

To model the effects of vegetation (and bank stabilisation treatments) a lumped ∝ factor can be included in the excess shear stress equation to indirectly correct the applied shear stress (Daly et al., 2015):

$$\epsilon_r = \boldsymbol{k_d(\alpha\tau - \tau_c) = \alpha k_d(\tau - \frac{\tau_c}{\alpha})}$$

The bank stability component of BSTEM calculates a factor of safety (FoS) for planar- or cantilever-shear failure in a layered streambank based on force-equilibrium analysis. Where FoS is the ratio of driving forces to resisting forces for a specified failure plain. Driving forces include the weight of the failure plane (reduced by a component of the hydrostatic forces of stream flow), while resisting forces include pore pressure, cohesive strengths of soil, shear strength provided by vegetation, and the confining hydrostatic forces (Simon et al., 2010). The FoS is calculated based on horizontal soil layers, vertical slices and cantilever failures (Klavon et al., 2017). Mass failure is assumed to occur when the driving forces applied to a stream bank exceed the resisting forces, that is when FoS is less than one (Daly et al., 2015). An iterative approach is used to determine the failure plane with the lowest FoS. By coupling the bank stability and toe erosion models BSTEM allows feedback between hydraulic and geotechnical processes. For example, fluvial scour may reduce the length of the failure plain and decrease the FoS of the critical failure plain, thereby exacerbating risk of failure (CEIWR-HEC, 2015).

Model input parameters

Parameters required to evaluate geotechnical stability include bank geometry and layering, flow conditions, effective cohesion, angle of friction and the saturated hydraulic conductivity. Bank vegetation and toe protection parameters also inform bank stability (vegetation reduces near-bank velocity, thereby improving bank stability). For HEC-RAS BSTEM model set up geometry and flow data are required (Table 7).

Table 7. HEC-RAS BSTEM model set-up input parameters

Parameter	Unit	Description
Bank geometry	-	Cross-sectional terrain data
Flow data	m^3/h	Hourly streamflow data is used to generate event hydrographs

Soil strength parameters are used in the computation of the critical failure plane and the FoS of that failure plane. These intrinsic soil parameters are determined via standard geotechnical measurements. HEC-RAS BSTEM soil strength input parameters and data sources are listed in Table 8.

Table 8. Soil strength input parameters

Parameter	Unit	Description	Data source
Saturated unit weight	kg/m^3	Saturated weight of soil divided by total volume of soil.	Geotechnical assessment
Friction angle	°	Effective internal angle of friction	Geotechnical assessment

Cohesion	kPa	Attractive forces of particle with a soil matrix.	Geotechnical assessment
Phi b	°	Slope of the relationship between matrix suction and shear strength of sediment.	Estimated. Generally, between 10 - 15°
Bed graduation	diam (mm)	Bank material bed graduation – used to partition failed bank material into classes for transport by the sediment transport model	Geotechnical assessment

Erodibility parameters are specific to bank failure analysis. These parameters are measurements of the erodibility of the stream bank material in response to hydrodynamic forces (CEIWR-HEC, 2015). Most soil testing laboratories are unable to collect the parameters. These can, however, be measured in the field using an in-situ jet tester and a borehole shear tester (Simon et al., 2011). However, parameters may be estimated based on characteristic values (using data sheets) and/or model calibration. HEC-RAS BSTEM soil strength input parameters and data sources are listed in Table 9.

Table 9. Erodibility input parameters

Parameter	Unit	Description	Data source
Critical shear stress	Pa	Critical shear stress represents the value above which bank scour occurs. Where, shear stress is force applied divided by the cross-sectional area parallel to applied force.	Characteristic values and/or calibration
Erodibility	m^3/N-s	The rate of sediment removal in response to unit shear stress.	Characteristic values and/or calibration
Treatment critical shear stress	Pa	Based on treatment e.g. vegetation at different levels of maturity	Previous studies

Applicability to GBR streams and limitations

Comparative studies

The BSTEM model have been applied to a range of systems within Queensland including within the GBR catchments. Brooks et. al. (2014) compared HEC-RAS BSTEM modelled stream bank erosion at sites along the Upper Brisbane River to observed bank erosion (based on LiDAR analysis). The model was applied at sites for which detailed sedimentologic and channel hydraulic data was available. BSTEM was found to significantly over estimate bank erosion.

In contrast, Simon (2014) compared BSTEM (excel) long term bank erosion rates along the lower Burnett River with 2009-2013 rates estimated using aerial imagery. The long-term annual bank erosion rate was approximately 3.1 MT/y, which was approximately half the rate predicted using aerial imagery (6.1Mt/y). This suggests a considerable improvement on the bank erosion rate predicted by SedNet, which along the lower Burnett River was approximately 18 times less than the rates predicted by BSTEM. However, Baheerathan et.al. (2017) claims the opposite after comparing modelled results from both modelled results against loads estimated by Great Barrier Reef Catchment Loads Monitoring Program (GBRCLMP).

Alluvium (2014, 2015, 2019) developed BSTEM models for sites in the Logan River, Laidley Creek and Mary River. These models were based on pre- and post-flood cross-section data and flood hydrographs. Through an extensive calibration process good matches between pre and post flood bank morphology was achieved at the site scale.

Variety of river typologies

BSTEM is only suitable for stream banks with horizontal floodplain stratigraphy with up to five distinct layers which is typical of self-formed meandering rivers. The model assumes simple channel cross section, and that stream bank and floodplain sediments are relatively uniform and can be characterised by simple flood plain processes. However, many rivers in Queensland are dominated by complex macro-channel morphology characterised by oblique accretion units and complex non-horizontal stratigraphy (Brooks et al., 2014). This oversimplification of channel morphology and bank erosion processes limits BSTEM's capacity to accurately predict bank erosion rates and distribution in many of the GBR catchments.

Site scale model

BSTEM is a deterministic model used to predict stream bank erosion at a site scale. It requires substantial site-specific parameterization of bank sedimentology and geomechanics. Currently there is no accurate method for predicting stream bank sedimentology using remote sensing. Therefore, the model can only be applied where detailed bank stratigraphy and geotechnical data has been collected (Brooks et al., 2014). Due to the spatial variability of sedimentology the model may significantly under- or over-estimate stream bank erosion if extrapolated from one site to another without detail field-based parameterisation. Furthermore, to achieve good model performance significant calibration to known flow events is required.

Brooks also identified limitations in terms of extrapolating BSTEM from site to reach scale. The Percent Reach Fail (PRF) method is frequently used to extrapolate site specific bank erosion data to the reach scale based on the proportion of the stream that has a visual appearance of bank failure/erosion. However, the PRF approach has limited predictive power in rivers with macro-channel morphology. Along the O'Connell River, for example, Brooks (2014) found a weak linear correlation between observed bank erosion length and the predicted erosion length using the PRF method.

Erosion mechanisms

BSTEM has been widely used to predict fluvial erosion and gravitation mass failure (both planar and cantilever) associated with multilayered streambanks in different river systems. Other mechanisms of gravitational failure (i.e. rotational and wet-flow failures) prevalent in GBR streams are not predicted by BSTEM. Furthermore, many streams in the GBR catchments have a compound channel morphology with multiple depositional surfaces which can be formed through oblique accretion rather than the horizontal layers required in BSTEM. The applicability of BSTEM in these systems is likely to be limited as fluvial scour can occur along both the toe and surface of the depositional unit within the channel.

Vegetation growth

BSTEM assumes riparian vegetation grows on the top of bank, thus root density (and level of structural reinforcement) declines exponentially with depth. However, many native Australia vegetation species grow on the bank face and thereby provide additional resistance against mass failure (Brooks, et.al., 2014).

Summary and research opportunities

The BSTEM model is designed to predict stream bank erosion at a site scale. In systems where the bank morphology does not contain inset units and site-specific bank sedimentology and hydrological information is available it is an excellent tool for bank erosion prediction. Although a calibration process is often required to obtain a good match between modelled and observed data.

The expansion of the BSTEM model across the GBR catchments including the extrapolation of site-based results to the reach scale presents several issues. These include:

- BSTEM is very sensitive to local geotechnical properties. However, in GBR stream there is often large variations in erodibility longitudinally along the reach. As a result, it is very problematic to make uniform assumptions of sediment erodibility across large spatial areas.
- BSTEM is very sensitive to local hydraulic properties and typically requires hourly flow data and high resolution channel cross-section dimension and slope data (e.g. 1m resolution). In many streams in the GBR this level of information is not available.
- Unsuitable for macro-channel systems with inset depositional units, often dominated by complex oblique accretion.

2.4 Stream type based approach and multi-temporal analysis

Description of the approach
An alternative approach to streambank erosion prediction is proposed for the GBR catchments. This proposed approach is yet to be applied but draws on components of other approaches that have been developed and applied in Queensland including the approach proposed by Brooks et. al. (2014). The key principles which have guided the development of this approach are:

- There are a variety of river types within the GBR catchments. In each of these different systems the factors that impact and/or drive channel erosion processes are likely to differ. It will be difficult to accurately predict stream bank erosion without understanding the spatial distribution of each river type and processes that impact erosion in each system.

- Multi-temporal LiDAR analysis needs to play a key role in assessing erosional processes in each river type. This data should be used to train coarser resolution remotely sensed data to extrapolate to other areas of the same river type.

The proposed approach would have the following key steps:

1. River typology assessment across the region based on a standardised assessment approach.

2. Identification of representative reaches of each river type where either multi-temporal LiDAR data is available or can be collected.

3. Assessment of erosional processes within each representative reach against channel parameters such as bank height, foliage coverage and channel slope etc.

4. The use of self organising maps and the LiDAR analysis to train coarser resolution remotely sensed data to enable extrapolation to other areas of that river type.

5. Developing a relationship between flow and erosion based on the flow record between the two LiDAR datasets.

Further details on each of the proposed steps is outlined below. The proposed approach has only been developed to a conceptual level. Further work would be required to refine each step.

Step 1 - River typology assessment
A river typology assessment for a GBR catchment (or all catchments) should be undertaken based on desktop geospatial analysis of available aerial imagery, topographic data and other spatial data (i.e. geology, soils etc.). The desktop assessment should be verified through a targeted field work program.

The approach for the assessment should draw on many aspects of other assessments such as RiverStyles™ (Brierley G, & Fryirs K, 2005). However, the method needs to address specific issues within GBR catchments. The approach must recognise that many rivers in GBR catchments do not necessarily have a 'classic' floodplain morphology and do not behave like true self-formed alluvial rivers. Many rivers in GBR catchments (i.e. Normanby River, Burnett River, O'Connell River, Burdekin River, Mary River) have a compound channel morphology bounded by resistant old floodplain/terrace deposits. Within the macro channel an inset channel and a range of geomorphic units (e.g. bars, benches, islands, inset floodplains) can exist. Stream banks which abut these resistant floodplain/terrace units may appear alluvial but often exhibit a control on the channel akin to bedrock. Understanding the distribution and degree of control provided by these resistant floodplain/terrace units will be a critical component of any river typology assessment.

An example of a river typology assessment undertaken of the Mackay Whitsunday region is shown in Figure 13 (Alluvium,2015). This assessment identified considerable lengths of streams which were confined by resistant floodplain/terraces. In the major flood events associated with Cyclone Debbie in 2017 these reaches experienced minimal channel change. Under a typical RiverStyles™ assessment these reaches would be classified as unconfined alluvial systems and would be considered vulnerable to lateral channel change. This highlights the importance of incorporating the degree of floodplain/terraces in any river typology assessment.

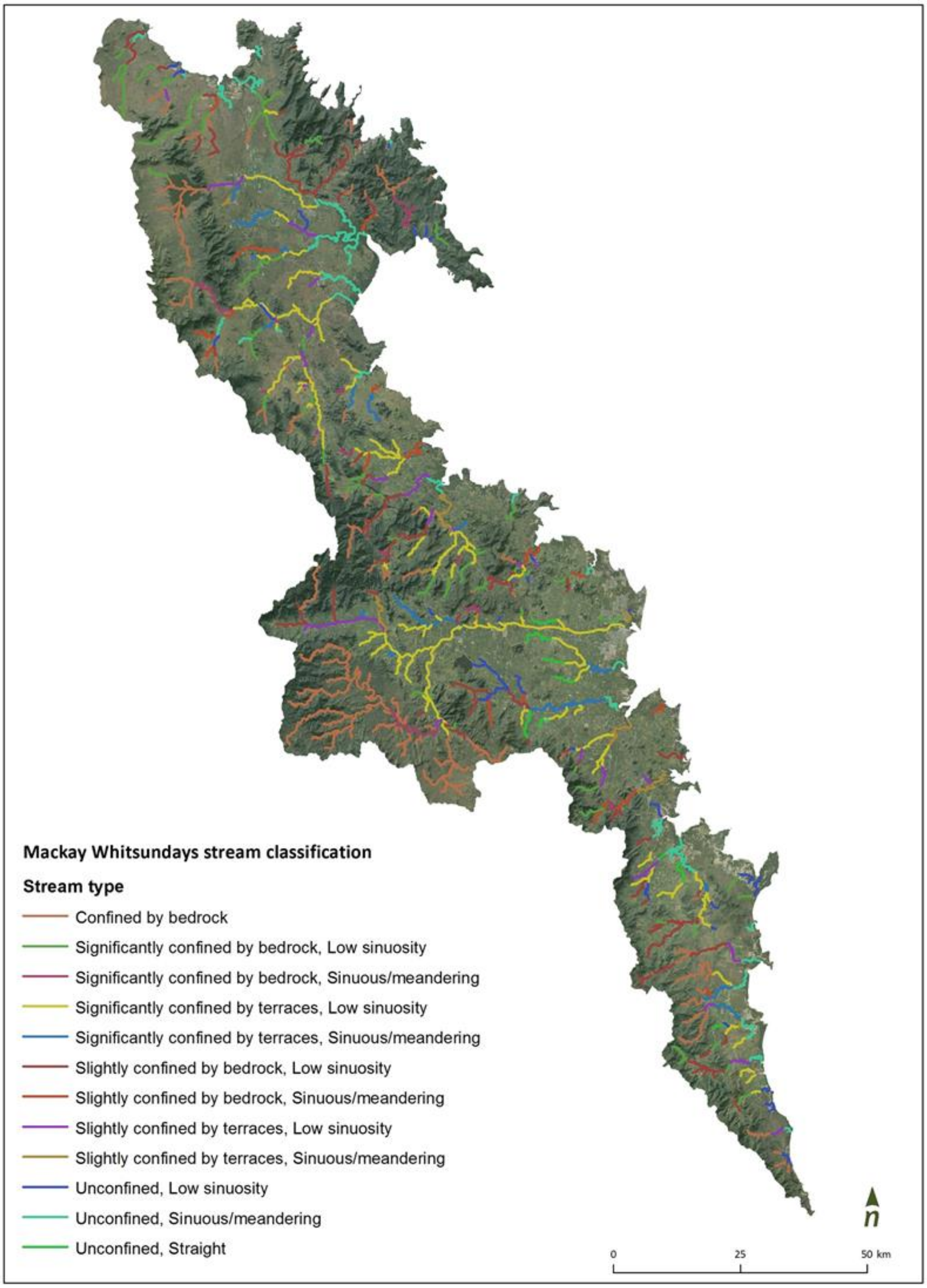

Figure 13. *Examples of river classification undertaken of the Mackay Whitsundays region*

Step 2 - Identification of representative reaches

Representative reaches of each major river type in the region should be selected based on condition and biophysiographic properties. For streams within the GBR catchments specific river types may include:

- Unconfined meandering systems which have a self-formed floodplain

- Compound channel systems with varying degrees of floodplain/terrace confinement
- Unconfined anabranching river reaches
- Smaller secondary channels

Selection of the representative reaches should also consider data availability (i.e. is LiDAR available?) and riparian condition (i.e. is the condition representative of the river type in the region?).

Step 3 - Assessment of erosional processes
For each representative reach LiDAR analysis should be undertaken to determine the most appropriate variables with potential predictive power for bank erosion (i.e. bank height, channel slope, upstream area and vegetation cover etc.), which may vary based on the river type. This would follow a similar approach as Brooks et. al (2014) in the Normanby catchment (Figure 14). In this study, a nonlinear correlation matrix analysis determined the correlation between geomorphic units, LiDAR derived parameters and erosion. The proposed method enables the calculation of correlation values between continuous variables and categorical variables in order to identify geomorphic units most prone to erosion.

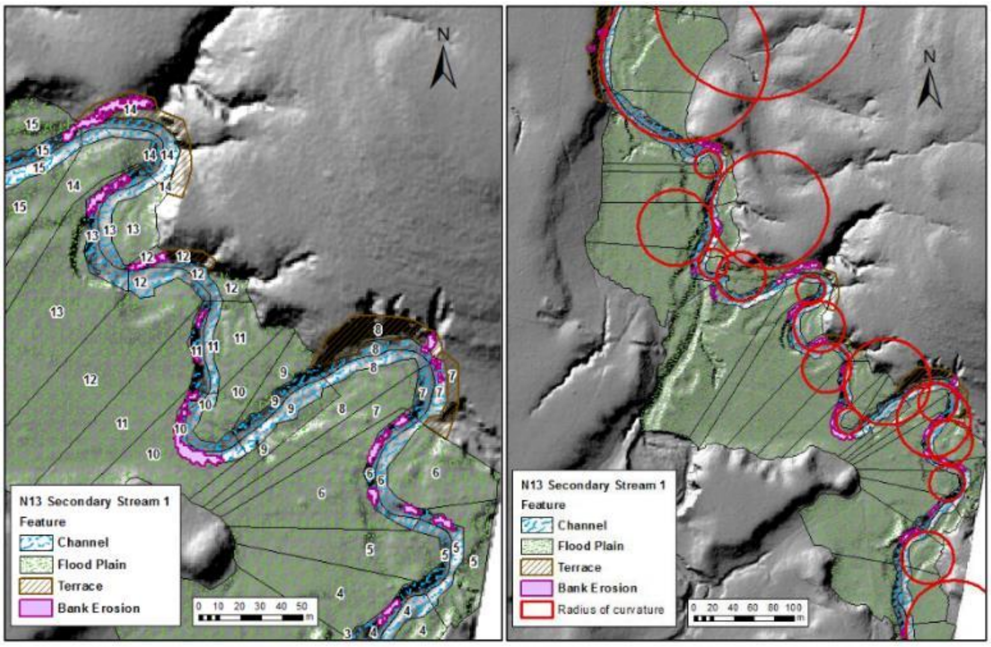

Figure 14. Example of geomorphic features/units, reaches and radius of curvature in a LiDAR block (from Brooks et. al., 2014)

Step 4 - Catchment scale model training
The variables identified in Step 3 as having high predictive power in each representative reach are then used to train coarser resolution remotely sensed data (e.g. 30m DEM etc.) in order to predict bank erosion in that river type. This approach was developed and tested in the Normanby River in Brooks et. al (2014).

In the Normanby River study, high resolution datasets were used to characterize catchment scale predicting variables. These dataset were then integrated into the reaches captured by LiDAR data to develop correlation between the catchment and reach scale predictive variables. Finally, a Self-Organising Maps (SOM) model was used to develop the reach scale potential erosion map (Figure 15 and Figure 16). A SOM is a subcategory of the artificial neural network algorithms which can be used to illustrate nonlinear correlations between datasets with high dimensionality (Brooks et. al., 2014).

A similar approach is recommended for each river type.

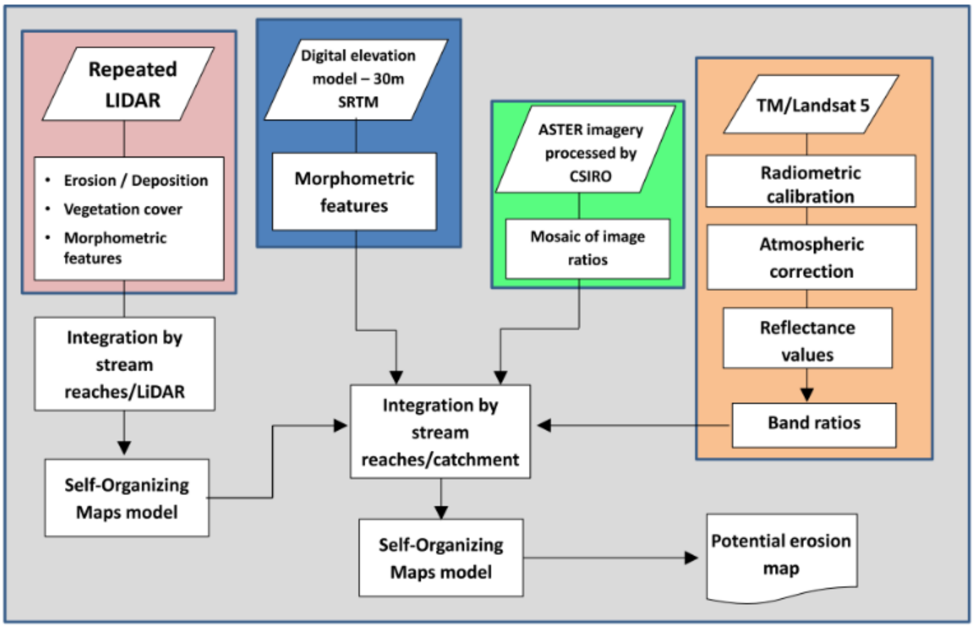

Figure 15*. Flowchart of upscaling process adopted in the Normanby River study (from Brooks et. al., 2014)*

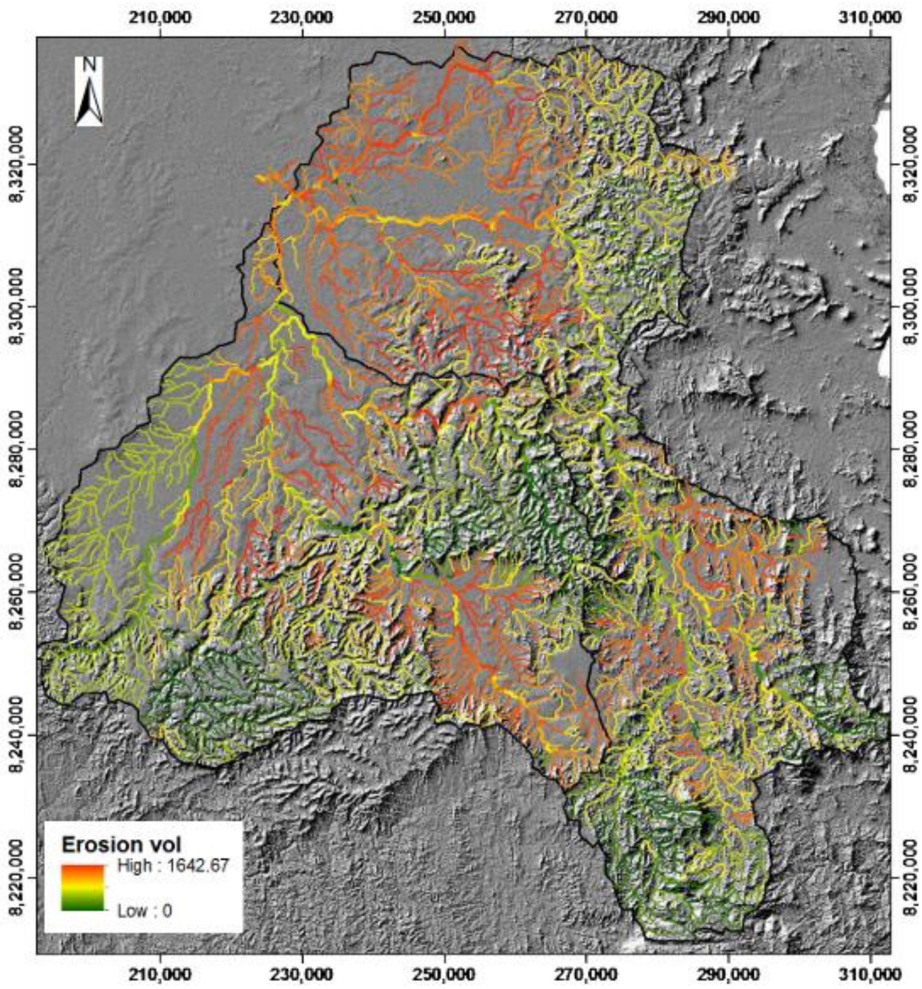

Figure 16*. Model output: map of predicted erosion volumes in the Normanby catchment (from Brooks et. al., 2014)*

Step 5 – Correlation between flow and erosion
The magnitude of erosion determined in Step 3 within each representative reach would largely be driven by the flow regime between the two LiDAR datasets. This step aims to determine some correlation between the flow and observed erosion. This may involve estimation of cumulative stream power and developing a relationship between total work and erosion. This would allow the proposed approach to be integrated into catchment models where flow is a key input variable.

Summary and research opportunities
This approach aims to overcome some of the issues identified in the other three models which aim to fit a 'one size fits all approach' to all streams in the GBR catchments. The streams of the GBR catchments are widely diverse and this approach, which aims to incorporate these differences into the model development, has several advantages.

While this approach is considered superior to the other models assessed it would require significant research and development before it could be implemented more broadly. This research and development would need to include collection of multi-temporal LiDAR data, development of a river typology assessment approach and model development, testing, calibration and validation.

In some areas of the GBR catchments the multi-temporal datasets required for this approach already exist. There is an opportunity to start implementing this method in these areas while data is collected in other catchments.

3 Summary

This review has highlighted the difficulties in predicting stream bank erosion across the broad catchments of the GBR. Stream bank erosion processes are complex, often non-linear, and involve a range of diverse and interrelated variables. As a result, selecting an appropriate predictive model is very challenging, especially at the scale of the GBR catchments where data availability is limited.

Several research opportunities have been identified in this review (Table 10). While Dynamic Sednet continues to be used to assess end of catchments loads in GBR catchments there are several knowledge gaps which should be addressed. These include assessing the applicability of the model to different river types, improved stream power and erodibility determination and a framework to assist in developing confidence bands based on the river type and data availability. Many of these research needs were identified in Prosser (2018).

The BANCS model offers advantages to the current approach as it is designed to model erosion at the required reach scale based on local remotely sensed and field data. However, opportunities for broader expansion into the GBR catchments may be limited due to the data requirements and uncertainty around its applicability to the hydrologic regimes of GBR catchments and different river types.

BSTEM is generally applicable to the site scale and requires extensive data collection. Furthermore, the model is not applicable to many GBR rivers with a compound channel morphology. As a result, there is limited opportunities to use this model in GBR catchments to predict catchment loads.

Finally, an alternative approach is proposed which specifically incorporates a river typology assessment. In this approach, high resolution multi-temporal LiDAR data is used to train coarser datasets for each river type. However, of all the approaches assessed this one would require the greatest level of research and development before it can be more broadly applied to a GBR catchment.

Developing a framework for the river typology assessment is a critical component of the approach outlined in Section 2.4. However, such a framework would add significant value to all stream bank modelling approaches including the existing Dynamic Sednet approach. Stream bank erosion process are likely to vary in different river types. Understanding the spatial distribution of each river type and processes that impact erosion in each system will provide significant benefit to modellers no matter which approach is adopted.

Table 10. Summary of the four approaches reviewed and research opportunities

Model	Summary and limitations	Research opportunity
Dynamic SedNet Stream Bank Erosion model	Existing model used in Paddock to Reef program. Limited predictive power at the reach or sub-catchment scale without significant calibration	Numerous research opportunities were identified in Prosser (2018). Key knowledge gaps include applicability to different river types and stream power determination approach.
Bank Assessment of Non-point Source Consequence of Sediment (BANCS)	Potential to significantly improve stream bank erosion prediction in certain river types. Significant limitations identified which may impact the applicability of the model to the broader GBR catchments.	Test approach in certain river types in the GBR. Investigate approaches to limit the requirement for field investigation by using remote sensing data.
The Bank Stability and Toe Erosion Model (BSTEM)	Good site based erosion model in certain river types when appropriate data is available. Limited opportunity to extrapolate results to the reach scale.	No opportunity identified

Stream type based approach and multi-temporal analysis	Superior approach as it specifically considers the different erosion processes in each river type.	Development of a GBR specific river typology assessment approach.
	Requires significant data collection and research and development.	Model development, testing, calibration and validation in a specific catchment.

4 Workshop summary and report feedback

The results of this review were presented at a workshop with key project team members, DES staff and members of the steering committee. The workshop was held on the 17th of October and was attended by:

- Misko Ivezich (Alluvium)
- Marnina Tozer (Alluvium)
- Andrew Brooks (Griffith University)
- James Daley (Griffith University)
- Jenny Riches (DES)
- Sarah Stevens (DES)
- Maria Askildsen (DNRME)
- Robin Ellis (DES/Steering committee member)
- Rebecca Bartley (CSIRO/ Steering committee member)
- Chris Thompson (Seqwater/Steering committee member)

Key feedback compiled on this report and the workshop presentation is presented in Table 11. Key points and recommendations for the remainder of this project from the project steering committee members is presented in Table 12.

There is generally broad agreement with the findings of this report with regards to the limitations with both BANCS and BSTEM from steering committee members. This review concluded that these models are unlikely to provide significant improvement in broad-scale bank erosion prediction in Queensland.

All steering committee members agreed there is value in exploring the development of a river typology approach for GBR rivers. The river typology approach could assist in a range of modelling endeavours including:

- Assisting modellers in the parameterisation and understanding of processes within the existing SedNet/Source modelling framework
- Forming the basis for new modelling approaches including the stream type based approach outlined in this report.

In addition to these modelling benefits the approach could greatly assist river restoration planning and design endeavours which are widespread across the GBR catchments.

Based on the findings of this report and feedback from the steering committee it is recommended that this current research project be rescoped to focus on the development of a river typology approach. Key stages could include:

- **Stage 1 – Background review:** Review of international river typology approaches to assess their strengths and weaknesses and components that would be applicable to the GBR catchments.
- **Stage 2 – Stakeholder engagement:** Engage with key stakeholders including a workshop with steering committee members and technical experts to determine the key objectives, components and scale of the river typology approach.
- **Stage 3 – Development of river typology framework**: Based on outcomes from the stakeholder workshop develop a framework for the river typology approach considering major channel controls and process domains.

- **Stage 4** – **Application of river typology framework:** Apply the assessment approach to a small sub-region within the GBR catchments.
- **Stage 5 – Development of conceptual models**: For the main river types identified in the framework develop conceptual models which identifies key controls, sediment supply, transport and storage processes, bank erosion processes and channel evolution processes.
- **Stage 6 – Recommendations:** Outline key recommendations relating to:
    - The use of framework and conceptual models to inform existing SedNet modelling
    - The further development and expansion of the framework across the GBR catchments
    - The development of new modelling approaches based on the river typology approach as outlined in this report

If this revised approach is endorsed by the Queensland Water Modelling Network a more detailed method and project plan can be developed.

Table 11. Summary of the four approaches reviewed, research opportunity and key points discussed

Model	Application scale	Summary and limitations	Report feedback and/or workshop discussion
Dynamic SedNet Stream Bank Erosion model	Catchment scale	Existing model used in Paddock to Reef program. Limited predictive power at the reach or sub-catchment scale without significant calibration	• Opportunity to develop a new methodology for parameterising erodibility (James). • Some uncertainty of how gullies and streambanks are modelled in Sednet. Currently streambanks are represented crudely (Rob). • SedNet is the only approach that can be used without specific field measurement data, however, it has been shown that the accuracy can be greatly improved with field data (Rebecca). • SedNet was not designed and constructed for (a) the type of channels in GBR, (b) the hydrologic variability of channels in the GBR, and (c) how the flow regime interacts with the channels types to effect the different erosion processes of fluvial erosion (stripping inset features, bank erosion), range of bank mass failure processes (cantilever failure, wet flow etc.) and subaerial erosion. A stream type approach could feed into SedNet to determine different parameters of a model to be applied for different links representing different channel types (Chris).
Bank Assessment of Non-point Source Consequence of Sediment (BANCS)	Reach scale although one model can be used across all similar reaches within hydrophysiographic region	Potential to significantly improve stream bank erosion prediction in certain river types. Significant limitations identified which may impact the applicability of the model to the broader GBR catchments.	• BANCS similar to rapid geomorphic assessment (RGA) qualitative survey approach (Andrew). • High level of detail required to get adequate inputs to model and if same effort was put to refining SedNet parameters then could expect similar levels of uncertainty in modelled results (Chris). • NBS model parameters 1 & 2 (especially) not appropriate for many of Qld channels. Parameters 3 – 6 requires either detailed analysis or to be modified to such an extent that high uncertainty would result (Chris). • Only applicable to calibration flow regime (Chris). • A lot of effort required for probably no significant gain over SedNet in precision and uncertainty (Chris). • Likely to face the same issues as seen in empirical models previously applied.
The Bank Stability and Toe Erosion Model (BSTEM)	Site scale	Good site-based erosion model in certain river types when appropriate data is available. Limited opportunity to extrapolate results to the reach scale.	• Effective at a site-based level. Difficult to scale up.
Stream type based approach and multi-temporal analysis	Catchment scale	Superior approach as it specifically considers the different erosion processes in each river type.	• Opportunities with development of a GBR specific river typology assessment approach. • More valuable if not categorised too finely (Rebecca). • The typology and intensive data approach allows us to consider in-channel processes as well as stream banks, which is an advantage (Rob)

	Requires significant data collection and research and development.	• Outcome could be a decision support framework / risk-based framework approach with proof of concept for one or two catchment (Andrew, Chris). Heterogeneous catchment such as Fitzroy catchment may be a good option (Rebecca). • The conceptual approach does build upon previous research. By incorporating the river typology component into the intensive data analysis it has aligned the conceptual approach more closely with some of Prosser's recommendations (Rob). • Opportunity to draw upon the experience of the expert that has designed the bulk of the data analysis (Brooks), the contribution by acknowledged experts continues to give the project rigour (Rob) • Typology approach could feed into SedNet and assist modellers • Opportunity for phased rollout as data is generated for each catchment (Andrew).

Table 12. Steering committee key point discussed and future directions

Steering committee member	Key points and recommendations
Robin Ellis	Key points • Literature review on BANCS and BSTEM demonstrated that they both have limitations in terms of improving broad-scale bank erosion models being used in Queensland. • Proposal to properly investigate the typology and intensive data approach as an alternative modelling approach is in keeping with the broad intent of the original proposal. • The typology and intensive data approach allows us to consider in-channel processes as well as stream banks, which is an advantage. • Opportunity to draw upon the experience of the expert that has designed the bulk of the data analysis (Brooks), the contribution by acknowledged experts continues to give the project rigour.
Rebecca Bartley	Key points • The reviewed models are not equal and have different roles (applicable at different scales). • There may be merit in creating a schematic diagram which shows that the relative error or uncertainty at the reach scale prediction of bank erosion is inversely proportional to the amount of field data acquired. • Could use SedNet to identify likely hotspots for bank erosion at whole of GBR scale, and then use another model to assess more quantitative reach scale dynamics. Key recommendations for development of typology: • Highlight the diversity of stream types in the GBR (lump up into like units but avoid too much splitting). • The typology should use ≤ 5 classes (i.e. straight, meandering, multi-thread, (bed-rock) constricted, incised (or similar). • Where possible the classification should be based on some quantitative predictor variables e.g. some element of discharge Q or sinuosity etc so that it can be predicted over large areas. Amos et al. (2008) has a nice approach to making sure the classification can be used in a Quantitative framework (see Figure 5 and 7).
Chris Thompson	Key points • A Stream typology framework is preferred. • Provides a framework for understanding processes and potential channel response trajectories, hence appropriateness of intervention strategies. Key recommendations for development of typology: • Scale of classification is key; too coarse and will miss key differences in processes. • Classification needs to incorporate main process domain areas, (i.e. source, transfer and sink, bank mass failure zones) as well as the channel type, dominant confining material (lateral – banks etc.) and constraining (bed) material. Key questions around development of typology: • Is there any mapping and classification of channel erosion types within any channels that can be used to guide channel-type specific erosion models? • Is there data on subaerial preparation/erosion contribution across any of the catchments. • What is the estimated ephemeral channel length in (SedNET-scale) upper sub-catchments that are not included as links/streams?

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