CHANNEL AND BANK STABILITY OF THE BURNETT RIVER IN THE AFTERMATH OF THE 2011 AND 2013 FLOODS: IMPLICATIONS FOR SEDIMENT DELIVERY TO THE GREAT BARRIER REEF

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Abstract The Burnett River, QLD Australia, experienced severe flooding in early 2011 and 2013, with the latter flood breaking all historical records. As a result, damage to infrastructure and the loss of agricultural land from bank erosion was considerable. Exacerbated by the floods is concern about sediment delivered to downstream locations including dams/weirs, and ultimately to the Coral Sea and the Great Barrier Reef (GBR). The primary objectives of this work were to: (1) provide strategies for cost-effective protection of local assets and (2) determine the relative contributions of bank sediment (particularly fine-grained material) to overall sediment loads to the GBR.

Analysis of aerial imagery between 2009 and 2013 revealed that a total of about 27.8 million m^3 (47.3 Mt) of materials were eroded from the banks of the lower 300 km of the Burnett River main stem (about 6.1 million m^3/y or 10.4 Mt/y). An equal volume is not delivered to the Coral Sea, as an unknown proportion is deposited on low-bank surfaces, beds, bars and floodplains. It can be assumed that the majority of the fine-grained materials is transported through the system Approximately 21 million m^3 (35.6 Mt) or about two thirds of these sediments were eroded from banks downstream of Paradise Dam while much of the hydraulically-controlled bank sediment eroded from reaches upstream of rkm 170 was trapped behind the dam (7.0 million m^3).

Long-term simulations (42 years) were conducted using the Bank Stability and Toe Erosion Model (BSTEM), to compare longer term averages with the 2009-2013 rates calculated from aerial imagery. Over this longer time period, annual bank-erosion rates are about 3.1 million Mt/y; about 18 times greater than the value predicted by the catchment model SedNet. Bank-erosion rates below Paradise Dam (rkm 131) are 2.4 million t/y. Assuming 100 years of simulation and using an empirical relation between the period of BSTEM simulations and calculated erosion rates, a conservative value for the average, annual rate of bank erosion is 2.0 Mt/y. Bank erosion, instead of being a minor source of sediment representing 8% of the total, was found to be the single largest contributor of sediment in the Burnett River Catchment, representing at least 44% of the total, annual sediment budget.

The implications of these findings are considered in the context of erosion sources and rates in Brodie et al., (2003) who report that on average, 2.75 Mt/y are eroded from the catchment. By replacing their 0.175 Mt/y from the banks with the 2.0 Mt/y calculated in this study, a new total of 4.6 Mt/y is obtained. Given these significant differences in both the relative importance and absolute rates of bank erosion than was earlier reported, sediment management should be re-focused to include this important source. Doing so would not only protect local assets by limiting land loss and bank retreat, but would help maintain reservoir and harbour capacity, minimize downstream flooding, and protect marine resources.

INTRODUCTION AND BACKGROUND

The Burnett River is one of the Reef Catchments flowing through the city of Bundaberg in its downstream reaches before exiting to the Coral Sea. The Burnett River experienced severe flooding in early 2011 and 2013, with the latter flood breaking all historical records. As a result of these floods, damage to assets, infrastructure and the loss of agricultural land from bank erosion was considerable. Massive amounts of sediment were transported to the Coral Sea (Figure 1). In an effort to develop a strategy for prioritizing and determining resilient and cost-effective protection measures, an understanding of both site-specific and system-wide stability conditions is essential. For site- and reach-specific solutions, this is accomplished by quantifying the driving (flow and gravitational) forces and resisting (shear strength) forces operating on the channel banks, and testing how alternative stabilization measures would perform over a range of flows. System-wide analysis then provides the spatial and temporal context of

channel instability to determine the suitability of conducting various types of channel works (i.e. energy dissipation, bank stabilization, etc.) to protect assets and to aid in prioritization of those works.

The geographic scope of this study extends from the mouth of the Burnett River east of Bundaberg, upstream about 300 km to Eidsvold (Figure 2). Results of this study will also be germane to managing sediment delivery from the catchment to the Coral Sea and the Great Barrier Reef by providing data on sediment contributions from streambank erosion.

Figure 1 Sediment plume from the Burnett River entering the Coral Sea, January 2013. Image provided by D. Honor (Bundaberg Regional Council; 2013).

FLOWS

This study was undertaken in the context of flood recovery following the record flows of January 2013. It is important, therefore, to put the magnitude and frequency of these kinds of devastating events in the perspective of the long-term flow record. Fortunately, the Burnett River has flow records extending back for more than a century. Annual-maximum peak flows from 1910 to present are shown in Figure 3 for the gauge at Walla Weir (136001A). Over the period, the flow of January 2013 represents the maximum recorded peak since 1910 and by definition, has a return period of at least 104 years. When viewed over the period of record, the 2013 peak is significantly greater (46%) than the previous maximum of 10,780 m^3/s recorded in 1942. In comparison, the 2013 peak was 157% greater than the peak flow in 2011. However, when the peak flows of 1890 and 1893 are considered, a slightly different picture emerges. Discharges for the large floods in 1890 and 1893 were estimated from stage data provided by Department of Natural Resources and Mines (DNRM; R. Maynard, written comm, 2013) and included in the peak-flow series. These flows represent the second and third largest flows since 1890, respectively, and demonstrate that the flood of January 2013 was (1) not that uncommon, and (2) only 17% greater than the estimated 1890 peak. By also considering the flood of February 1875 which had a peak 0.9 m below that of the 2013 peak at Bundaberg (DNRM, 2013), the return period for the 2013 flood reaches 139 years.

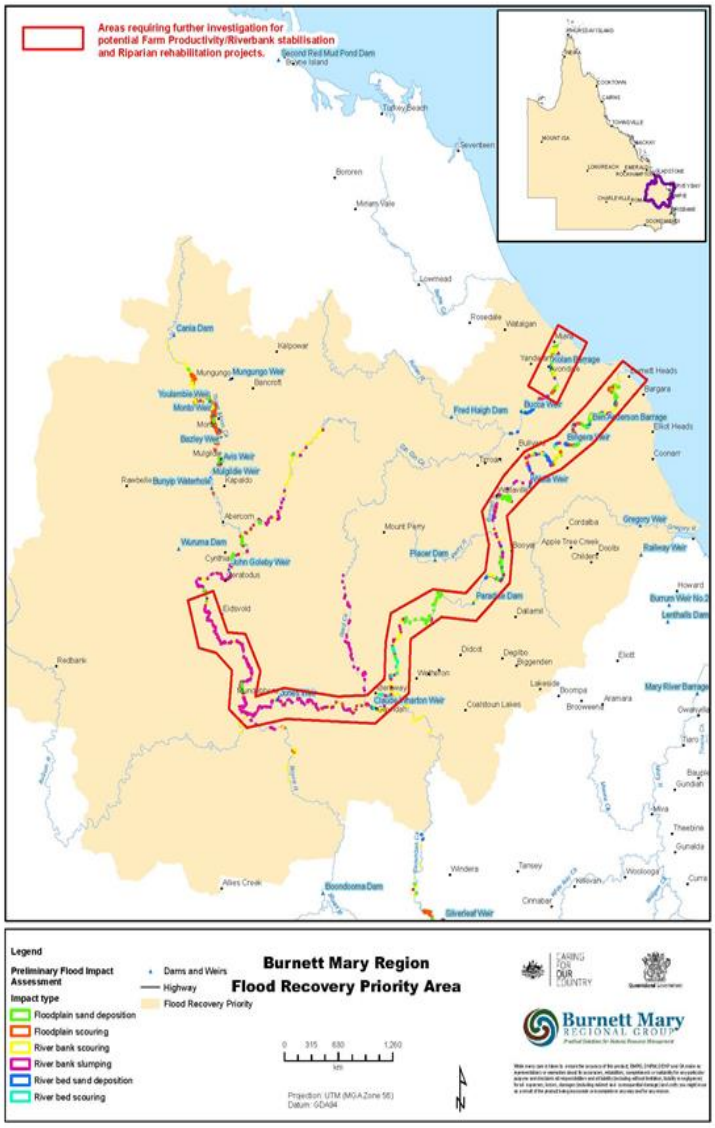

Figure 2 Geographic scope of the study along the Burnett River.

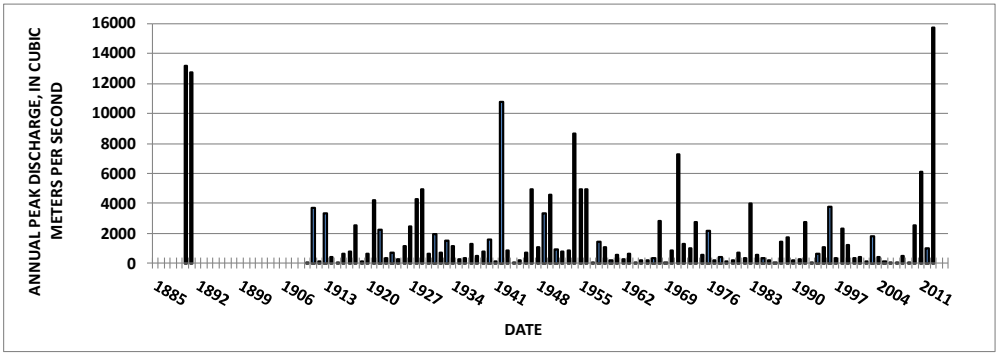

Figure 3 Annual maximum peak flows for the Burnett River at Walla Weir.

SYSTEM-WIDE STABILITY CONDITIONS

Analysis of current geomorphic conditions and dominant channel processes along the study reaches were conducted, in part through the use of Rapid Geomorphic Assessments (RGAs). RGAs utilize diagnostic criteria of channel form to infer dominant channel processes and the magnitude of channel instabilities through a series of nine, channel criteria. Inclusion of each criterion in the ranking scheme is founded on 30 years of research on the controlling forces and processes in unstable channels (Simon and Hupp, 1986; Simon, 1989; Simon and Downs 1995).

For each RGA, the dominant processes occurring along a reach were recorded using a Channel-Stability Ranking Scheme. Scoring for each criterion is such that a higher value indicates greater potential for erosion and instability. A maximum value of four (4) can be assigned to each, preventing subjective assumptions on the relative importance of each criterion. The nine criteria are directed at determining trends of recent channel adjustments through identification of the stage of channel evolution as impaired streams undergo a systematic adjustment (stages of channel evolution) as processes migrate through a channel network with time. To provide detail, the 2013 post-flood, aerial imagery of the reaches was analyzed over adjacent 2-km reaches to obtain information needed for the RGAs. The result is an almost continuous evaluation of channel conditions and dominant processes over 300 km of the Burnett River.

As hypothesized at the inception of this study, the effects of the impoundments on channel stability can be dramatic. The channel-stability index shows wave-like longitudinal variations, with peak values just downstream from the impoundments and other river-crossing structures. These effects attenuate (decrease) with distance downstream from each of the structures (Figure 4). The most unstable reaches are included in the orange fill (scores of 20-30) and are indicative of an incised channel with actively failing banks and limited vegetative cover over much of each of those 2-km reaches. Conversely, those reaches within the green fill (scores of 0-10) are generally stable with no active bank failures and generally good vegetative cover. The reaches with the most severe instabilities are located just downstream of Walla Weir and Paradise Dam where values of the channel-stability index are typically greater than 20 (Figure 4). Conversely, stable conditions extend upstream from these two impoundments; for 39 km above Paradise Dam (to rkm 170) and, for about 16 km above Walla Weir (to rkm 90). The stability imparted through the hydraulic effects of the dam extends about 20 km upstream of the head of the impoundment at rkm 150.

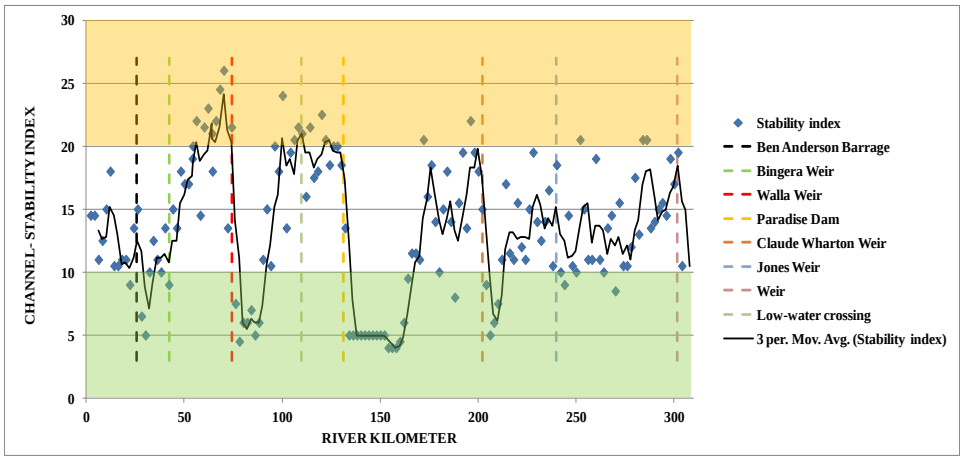

Figure 4 Longitudinal variation in the channel-stability index along the Burnett River main stem showing the effects of dams. Orange fill denotes very unstable conditions (20-30) while the green fill denotes very stable conditions (0-10).

Data on system-wide channel geometry (bank height, width, and slope) were obtained at 2-km increments from analysis of LiDAR data in those reaches where available. LiDAR coverages are not all from the same time, ranging from 2009 to early 2011. For the purposes of this study, it was assumed that they are all from one data set, representing the pre-flood condition of the channel. To determine the magnitude and extent of recent bank erosion, an analysis of the 2010 pre-flood and the 2013 post-flood, aerial photography was conducted. Fixed points on each bank were identified at 2-km increments in each paired image (2010 and 2013) to determine the distance from the

point to the top-bank edge. A comparison of the difference in these distances produced the amount of lateral retreat of the particular bank over the time period. Multiplying this value by the height of the bank provided the amount of material eroded per unit length of channel (in m^2/m). To then obtain an estimated value of the volume of sediment delivered to the channel by bank erosion, the average value between two adjacent reaches was then multiplied by the reach length (2,000 m).

BANK-DERIVED SEDIMENT LOADINGS

Unit bank-erosion rates provided information of the average amount of land lost to the river per unit length (m) of channel, but did not assume that each meter of a specific 2-km reach retreated at the same rate. This would only be the case if "percent reach failing" values obtained from the RGA analysis were 100%. Unit bank-erosion rates shown in Figure 5 again display the typical wave-like functions with peaks on the downstream sides of the impoundments.

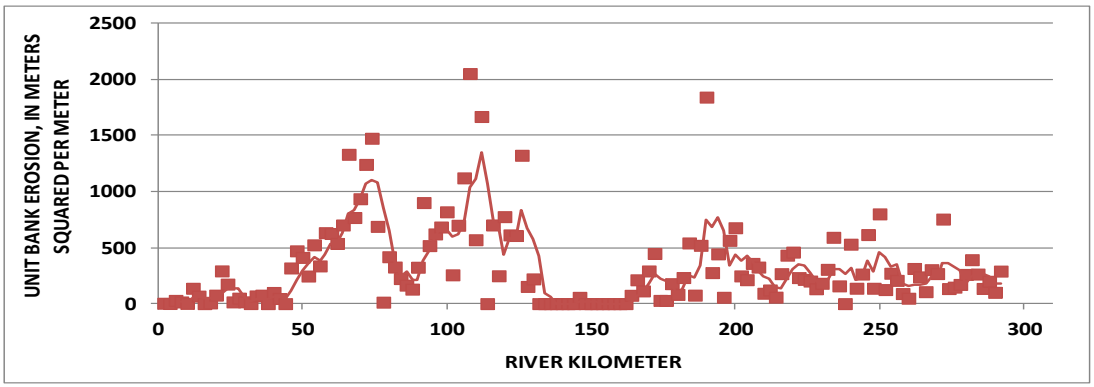

Figure 5 Unit bank-erosion rates, representing land loss (in m2/m) along the Burnett River main stem

To calculate total volumes of bank material eroded from the margins of the Burnett River, the unit bank-erosion rates for each bank, along each 2 km reach were multiplied by the "percent reach failing" (from the RGA data set) and by the reach length (2,000 m) (Figure 6).

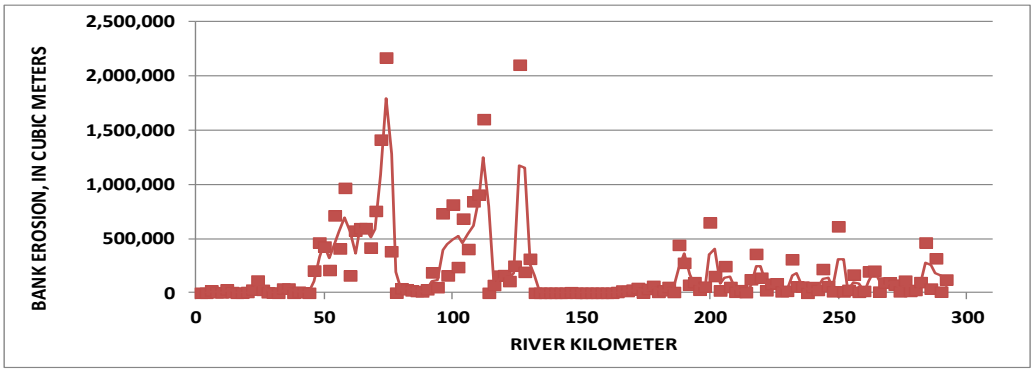

Figure 6 Volume of bank material eroded from floodplains and terraces along the Burnett River mainstem.

Summing the eroded-volume data along the entire 292 km reach of the Burnett River main stem gives a total volume of material eroded by bank processes of about 27.8 million m^3 (47.3 million t) or, about 6.1 million m^3/y (10.4 million t/y) over the 4.58-year modelling period. Erosion of these bank materials does not equate to an equal volume being delivered to the river mouth and the Coral Sea, as an unknown proportion is deposited on low-bank surfaces, beds, bars and floodplains. It can be assumed, however, that the majority of the fine-grained materials (silts and clays) are transported through the system and out to sea. Approximately 21 million m^3 (35.6 million t) or about two thirds of these sediments were eroded from banks downstream of Paradise Dam. One can assume that much of the

hydraulically-controlled bank sediment (less than 7 million m^3) eroded from reaches upstream of rkm 170 was trapped behind Paradise Dam. Erosion volumes are shown mapped in Figure 7.

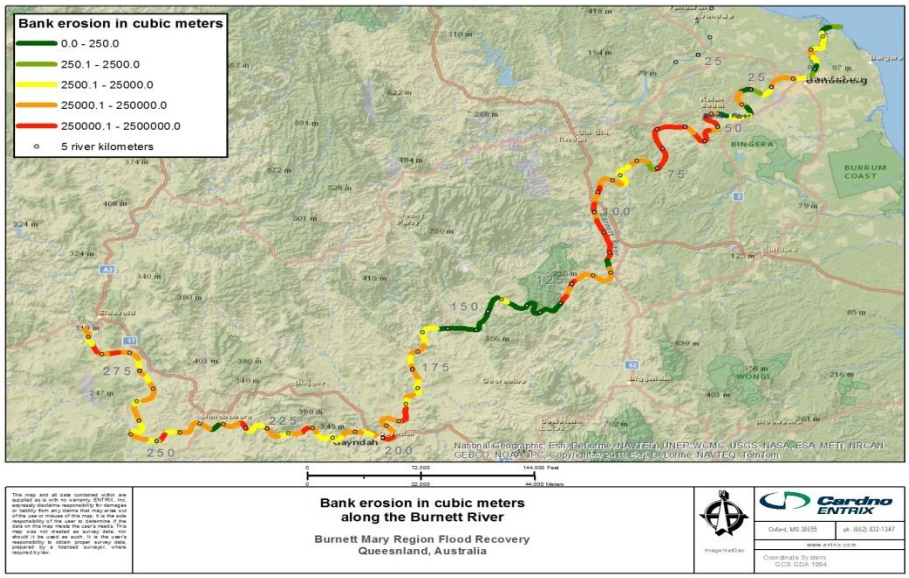

Figure 7 - Volumes of bank erosion over the period 2010-2013 along the Burnett River main stem.

Given these very high rates of bank erosion over the 2009-2013 period, it is important to place them in the context of longer-termed erosion rates and their implications for the management of sediment being delivered to the Coral Sea and the Great Barrier Reef (GBR). This is particularly germane to: (1) the Reef Rescue Program where conservation measures to reduce sediment delivery to the GBR are presently focused on upland and agricultural sources of sediment and not on streambanks, and (2) plans to dredge the lower Burnett River to reduce flood risks in Bundaberg.

Results of SedNet modelling in the Burnett River Catchment predict that on average, 175,000 t/y of sediment are eroded from banks of the Burnett River and its tributaries (Brodie et al., 2003). This represents about 8% of the predicted total amount of sediment erosion, with hillslope (1.6 million t/y) and gully (0.93 million t/y) sources making up the bulk of the total. Although it is unclear as to the length of the SedNet simulation period, we assumed that mean-annual flow was used to generate results expressed as "average annual" values. As a result of this large discrepancy between the SedNet results and those provided above, and its implications for sediment management, average, annual bank-erosion data were required for purposes of comparison.

AVERAGE ANNUAL RATES OF BANK EROSION: BSTEM MODELING

To obtain average, annual rates of bank erosion, values over a sufficiently long period of time were required. This was accomplished using numerical modelling. Geotechnical and hydraulic resistance of the bank and bank-toe materials were determined *in situ* at eight sites using conventional techniques (Iowa Borehole Shear Tester: Lohnes and Handy, 1968; Lutenegger and Hallberg, 1981, and the Submerged Jet-Test Device, Hanson, 1990; Hanson and Cook, 1997). Bank surveys and observations of stratigraphic layering for the tested banks were also obtained in the field. The field data were used with mean-daily flow data from gauges along the Burnett River to populate the Bank Stability and Toe Erosion Model (BSTEM-Dynamic 2.0; Simon et al., 2000) for the purpose of simulating bank-erosion rates over time periods ranging from about 4.5 to 42.5 years.

To obtain erosion results in units similar to those reported in Brodie et al., (2003), an average bulk unit weight of 1.7 kN/m^3 was used to convert m^3 to tonnes (t), resulting in a value of 47.3 million t of eroded bank sediment over the 2009-2013 period. This gives an average-annual rate of 10.3 million t over the 4.58-year simulation period. It is important to recall that this value represents 292 km of the Burnett River main stem and does not include bank erosion in the tributaries. Of course, it is unrealistic to use this average bank-erosion value because it represents a

short time period and a period of high and record flows. In order to make more direct and robust comparisons to the SedNet bank-erosion estimates, two steps were required.

First, bank erosion was calculated for the 292 km of main-stem channel using the BSTEM results from the mainstem sites over the 2009 to 2013 period. This necessitated the interpolation of erosion rates at the simulated sites to adjacent reaches and then summing them for the entire river. We then compared these results to the 47.3 million t that was calculated empirically to provide confidence in the methodology. Second, BSTEM was used again at the six sites to predict bank erosion over a longer time period. These results were then used to interpolate bank-erosion rates to adjacent reaches and to sum the values again. An average, annual bank-erosion rate was then obtained by dividing the result by the number of years used in the simulations. The resulting value was then compared directly with the results from SedNet. Unit bank-erosion rates were obtained for each of the six main-stem sites by modelling daily bank erosion over three periods:

- Calibration period (2009-2013) using 2009 as the starting geometry;
- Existing period (2003-2013) using 2013 as the starting geometry; and
- Long-term period (1971-2013) using 2013 as the starting geometry.

Overall, unit-erosion volumes for the 2009-2013 calibration period (in m^3 per length of channel) ranged from 40.5 m^3/m at the Gayndah (BMRG-06) site, to a maximum of 360 m^3/m at the Shalom College (BMRG-03) site. Bank-top retreat in the BSTEM calibration runs ranged from 4.70 m at the Eidsvold (BMRG-08) site, to 23.9 m at the Shalom College (BMRG-03) site (Table 1). It should be noted here that unit-erosion volumes are a function not only of bank-top retreat, but also of bank height.

In general, modeled bank retreat in the calibration runs corresponded reasonably well with the aerial- photography analysis and site-specific notes made in the field. Modeled rates of retreat during the calibration period were between -29% and 114% of those measured from the aerial photographs, with an average difference of 12%. In the case of BMRG-05, where the percent difference between measured and modeled bank retreat showed the highest percent difference (114 %). When the actual retreat values are compared, it can be seen that we are comparing bank retreat values of 2.94 and 6.29 m. Comparison of the aerial photographs from 2009 and 2013 for the entire reach showed however, that there is considerable variation in bank erosion along the reach, and a four meter difference between the two values could simply be a slight variation in field testing location versus digital measurement on the photographs. This percent difference at BMRG-05 is, therefore, not considered to be of concern and the calibration run is within a reasonable range for the reach.

Table 1 Unit erosion volumes for each site from BSTEM 2009-2013 simulations, and comparison with bank retreat measured from aerial photography.

Site	Unit Erosion Volumes from BSTEM (2009 to 2013) (m^3/m)	Bank Retreat from Aerial Photography (2009 to 2013) (m)	Bank Retreat from BSTEM (2009 to 2013) (m)	% Difference Between Measured and Modeled Bank Retreat
BMRG-02- Rubyanna	161	18.0	20.2	12.0
BMRG-03- Shalom	360	23.0	23.9	3.96
BMRG-04- Kolan	110	13.9	11.7	-15.8
BMRG-05- Wallaville	213	2.94	6.29	114
BMRG-06- Gayndah	40.5	6.01	6.19	3.00
BMRG-07-Munduberra	345	8.67	6.17	-28.8

BMRG-08- Eidsvold	81.9	4.89	4.70	-3.89

BSTEM results for each time period are shown in Table 2 and were then multiplied by the "percent reach failing" (obtained from the RGA analysis of each 2- km segment of the channel) and the reach length to obtain a volume of material eroded in each 2-km reach. Summing these values over the entire 292 km provided the volume of eroded material over 292 km of the Burnett River main stem. Unit-erosion values obtained for each of the sites were assigned over a reach extending halfway upstream and downstream to the next modelled site (Table 3). Values for the downstream-most site (BMRG-02; Rubyanna) at rkm 20 were extended to the mouth. Values for the upstream-most site (BMRG-08; Eidsvold) were extended to the top of the reach at rkm 292.

Table 2 Results of BSTEM-Dynamic 2.0 simulations for the calibration, existing and long-term periods.

Simulation period	Calibration	Existing	Longterm
Days	1673	3865	15529
Years	4.58	10.6	42.5
Site	**Eroded Volume (m^3/m)**		
BMRG-02	161	135	158
BMRG-03	360	783	1390
BMRG-05	213	252	625
BMRG-06	40.5	57.7	75.4
BMRG-07	345	528	665
BMRG-08	81.9	63.7	550

Simulation period	Calibration	Existing	Longterm
Days	1673	3865	15529
Years	4.58	10.6	42.5
Site	**Average Eroded Volume (m^3/m/y)**		
BMRG-02	35.2	12.8	3.72
BMRG-03	78.6	74.0	32.7
BMRG-05	46.5	23.8	14.7
BMRG-06	8.84	5.45	1.77
BMRG-07	75.3	49.9	15.6
BMRG-08	17.9	6.02	12.9

Table 3 Interpolation of unit-erosion rates calculated by BSTEM-Dynamic 2.0 at the main stem sites to adjacent reaches of the Burnett River main stem for the three simulation periods.

Site	River kilometer	Unit erosion (m^3/m)	Reach (rkm)
Calibration Period			
BMRG-02	12	161	0-32
BMRG-03	54	360	34-72
BMRG-05	91	213	74-146
BMRG-06	202	40.5	148-220
BMRG-07	239	345	222-260
BMRG-08	279	81.9	262-308
10-Year Period			
BMRG-02	12	135	0-32
BMRG-03	54	783	34-72
BMRG-05	91	252	74-146
BMRG-06	202	57.7	148-220
BMRG-07	239	528	222-260
BMRG-08	279	63.7	262-308
Long term Period			
BMRG-02	12	158	0-32
BMRG-03	54	1390	34-72
BMRG-05	91	625	74-146
BMRG-06	202	75.4	148-220
BMRG-07	239	665	222-260
BMRG-08	279	550	262-308

Results for the calibration period using interpolation of the BSTEM results showed that 25.1 million m^3 (42.7 million t) of bank erosion occurred over the 292 km-long reach. This value is about 10% less than the value obtained from the detailed empirical analysis of each 2 km segment and, therefore, provides sufficient confidence in the approach to utilize the 10-year and 42-year simulation periods to interpret long-term rates of bank erosion.

As one might expect, the empirical analysis showed greater longitudinal variability owing to data analysis of topographic data every 2 km (Figure 8). Average, annual bank-erosion over this 4.58-year period comes to about 5.5 million m^3/y (9.3 million t/y). The 10-year simulations, used to determine future erosion rates under "existing" (no action) and mitigated conditions represent a relatively short timeframe by which to compute long-term erosion rates. In this case, interpolation of the 10-year simulations at the six sites over the 292 km reach resulted in 39.5 million m^3 (67.2 million t) of bank erosion, with an average, annual value of 3.7 million m^3/y (6.3 million t/y). Details of these simulations (which include an analysis of the relative contributions from equal durations (5 years) of "wet" and "dry" periods) are included in the discussions of modelling results for each site. The bulk (about 90%) of the bank-derived sediment is delivered to the channel during the wet periods. However, it is important to note that the dry periods can still be effective at hydraulically eroding bank-toe sediments, thus making the bank more susceptible to further undercutting and collapse both during and after high-flow events.

The long-term simulations were conducted using a period slightly greater than 42 years (January 21, 1971 to July 31, 2013). This period was selected because it represented a timeframe covered by all of the gauges that were ultimately used to generate daily-flow data along the main stem. In our view, this was a sufficiently long period to determine average, annual bank-erosion rates. BSTEM simulations were again conducted for the six sites using daily time steps for this period. Results for the individual sites are shown in Table 3. Summing these results for each 2-km reach gives a total volume of bank erosion of 77.1 million m^3 (131million t). Dividing by 42.52 years gives an average, annual bank-erosion rate of 1.8 million m^3/y. Converting to tonnes produces a long-term rate of 3.1 million t/y over the 42 years of simulation, almost 18 times greater than the value predicted by SedNet. A value of 2.4 million t/y is calculated by summing just those reaches below Paradise Dam.

With all of the simulation periods including the peak flows of 2011 and 2013, it is not surprising that the calculated average, annual erosion rates decrease with increasing length of the simulation period. Plotting the calculated erosion rates against the length of the simulation period (Figure 9) shows this tendency. Because episodes of accelerated erosion are closely linked to high-flow years, it is essential, therefore, to use as along a simulation period as possible to accurately determine long-term, average-annual rates. Extrapolating the regression shown in Figure 9 to assume a 100-year simulation period gives an average, annual bank-erosion rate of 2.0 million t/y (from just the main stem channel), still more than an order of magnitude greater than the previous catchment-wide estimates from this source.

Brodie et al., (2003) reports that on average, 2.75 Mt/y are eroded from the catchment. By replacing the 0.175 Mt/y from the banks with the 2.0 Mt/y calculated in this study, a new total of 4.6 Mt/y is obtained. Assuming that the estimates from gully (0.93 Mt/y) and hillslope (1.65 Mt/y) sources are accurate, bank erosion becomes the single largest contributor, delivering 44% of the total sediment load; and once again, this does not include contributions from the tributaries. Brodie et al., (2003) further reports that average, annual total export of sediment from the Burnett River to the Coral Sea is 0.47 Mt/y, implying that 83% of all eroded sediment is deposited behind dams and on floodplain surfaces. Although this is a critically important parameter in estimating sediment export, it is beyond the scope of this investigation to verify that only 17% of the sediment eroded in the Burnett River Catchment reaches the Coral Sea and the GBR. Comparison of capacity surveys beyond structures such as Paradise Dam and additional LiDAR information with which to calculate floodplain-deposition would be valuable data used to validate and refine this parameter value. If however, we use a sediment-delivery rate of 17% with the improved predictions of bank erosion calculated in this study, a 66% increase in the export of sediment (0.79 Mt/y) is obtained. We assume that if erosion of bank sediments from tributaries were included in this analysis, that this figure would be even higher.

Bank erosion, instead of being a minor source of sediment representing 8% of the total (Brodie et al., 2003), has been shown to be the single largest contributor of sediment in the Burnett River Catchment, representing at least 44% of the total, annual sediment budget. In absolute terms, this is an increase in the average, annual rate of bank erosion from 0.175 Mt/y to 2.0 Mt/y. Given these significant differences in both the relative importance and absolute

rates of bank erosion than was reported earlier, sediment management should be re-focused to include this important source. Doing so would not only protect local assets by limiting land loss and bank retreat, but would help maintain reservoir capacity, minimize downstream flooding, reduce dredging costs, and protect marine resources.

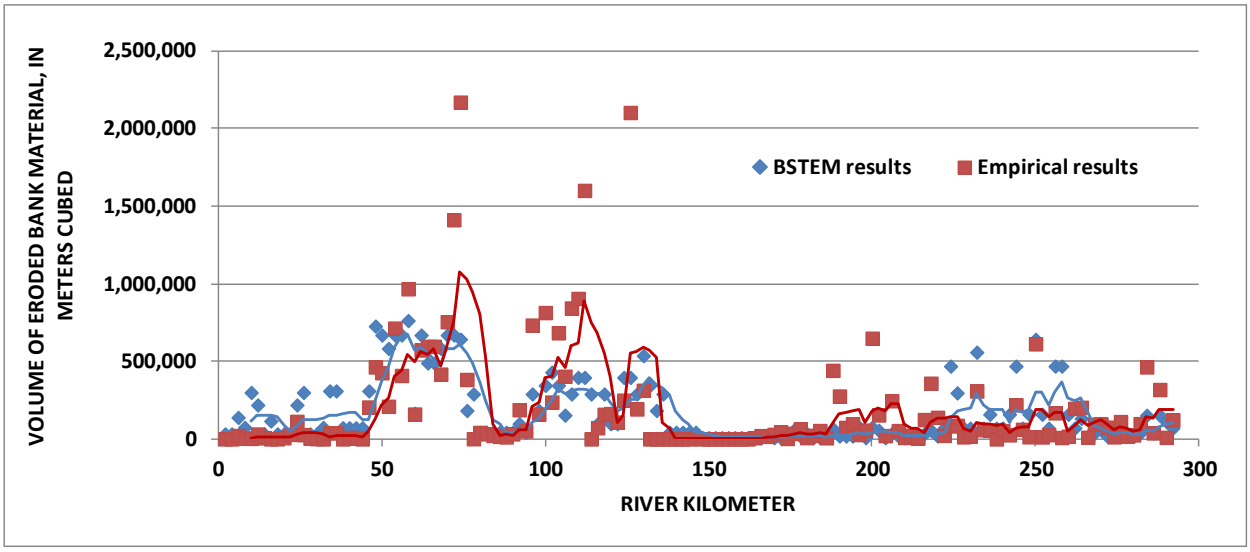

Figure 8 Comparison of bank-erosion volumes for each 2-km section of the Burnett River main stem as calculated from interpolation of BSTEM results and from analysis of LiDAR and air photo data over the 2009-2013 period.

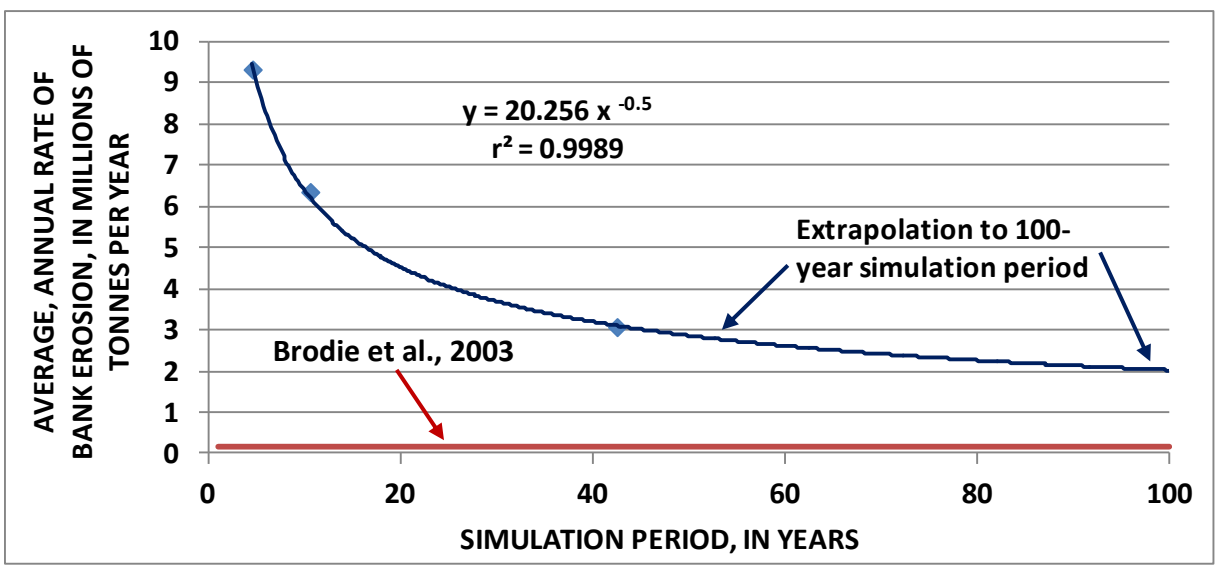

Figure 9 Comparison of average, annual bank-erosion rates (in millions of tonnes per year) for the Burnett River main stem derived from SedNet modelling (Brodie et al., 2003) and by interpolation of BSTEM results using different simulation periods.

SUMMARY AND CONCLUSIONS

Between 2009 and 2013 a total of about 27.8 million m^3 (47.3 Mt) of land were eroded from the banks of the lower 300 km of the Burnett River main stem. This translates into about 6.1 million m^3/y (10.4 Mt/y). Erosion of these bank materials does not equate to an equal volume being delivered to the river mouth and the Coral Sea, as an unknown proportion is deposited on low-bank surfaces, beds, bars and floodplains. It can be assumed, however, that the majority of the fine-grained materials (silts and clays) are transported through the system and out to sea.

Approximately 21 million m^3 (35.6 million t) or about two thirds of these sediments were eroded from banks downstream of Paradise Dam. One can assume that much of the hydraulically-controlled bank sediment eroded from reaches upstream of rkm 170 was trapped behind Paradise Dam (7.0 million m^3).
Long-term simulations (42 years) were conducted to determine average, annual rates of bank erosion. By again summing the results for each 2 km reach gives a total volume of bank erosion of 77.1 million m^3 (131 million t). Dividing by 42.52 years gives an average, annual bank-erosion rate of 3.1 million Mt/y, about 18 times greater than the value of 0.175 Mt/y predicted by SedNet. Bank-erosion rates below Paradise Dam are 2.4 million t/y. Assuming 100 years of simulation and using an empirical relation between the length of BSTEM simulations and calculated erosion rates, a conservative value for the average, annual rate of bank erosion is 2.0 Mt/y, and this does not include tributary contributions.

The implications of these findings are considered in the context of erosion sources and rates in Brodie et al. (2003) who report that on average, 2.75 Mt/y are eroded from the catchment. By replacing their 0.175 Mt/y from the banks with the 2.0 Mt/y calculated in this study, a new total of 4.6 Mt/y is obtained. Assuming that the estimates from gully (0.93 Mt/y) and hillslope (1.65 Mt/y) sources are accurate, bank erosion becomes the single largest contributor, delivering 44% of the total sediment load. Even using the 17% sediment-delivery rate reported in Brodie et al (2013), with the predictions of bank erosion calculated in this study, a 66% increase in the export of sediment (0.79 Mt/y) is obtained. We assume that if erosion of bank sediments from tributaries were included in this analysis, this figure would be even higher. Given these significant differences in both the relative importance and absolute rates of bank erosion then was earlier reported, sediment management should be re-focused to include this important source. Doing so would not only protect local assets by limiting land loss and bank retreat, but would help maintain reservoir and harbour capacity, minimize downstream flooding, reduce dredging costs, and protect marine resources.

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