ASSESSMENT OF FLOOD IMPACTS AND COST EFFECTIVENESS OF TREATMENTS TO MITIGATE EROSION, BURNETT RIVER, QUEENSLAND, AUSTRALIA

***Andrew Simon*[1]*, Natasha Bankhead*[1] *and Peter Wilson*[2]**

[1] *Cardno, P.O. Box 1236 Oxford, MS USA; andrew.simon@cardno.com*

[2] *Burnett-Mary Regional Group, 193 Bourbong Street, Bundaberg, QLD, 4670 AUS*

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 in Bundaberg and the loss of agricultural land from bank erosion was considerable. Exacerbated by the floods is concern about reducing sediment delivered to the Great Barrier Reef (GBR). It was determined that about 28M m^3 of material was eroded from the banks of the Burnett River making it the single largest contributor of sediment (as opposed to a minor contributor as was earlier reported) and causing re-evaluation of sediment management strategies.

Data on hydraulic and geotechnical resistance of the banks, along with daily flows were input to the Bank-Stability and Toe-Erosion Model (BSTEM) to predict bank-erosion with and without protection to determine the effectiveness of a range of mitigation measures. Alternative strategies that were simulated included combinations of rock facing, vegetative plantings, battering and the use of Bendway weirs or engineered log jams (ELJs). Although failures are responsible for the bulk of the material delivered to the river, reductions in bank steepening through toe protection or reductions in applied stresses from bendway weirs or ELJs result in significant reductions in erosion (40-99%). The planting of vegetation without additional toe protection or battering was not sufficient to reduce erosion rates. Overall, the scenarios involving rock in any form (rock toe or weirs) were the most expensive at any given site (about an order of magnitude higher than other measures at most sites, typically ranging from $1,000 to $3,000/m), and planting of vegetation was the least expensive (approximately $5/$m^2$ of bank face or top). In general, however, mitigation runs including a rock component provided the greatest level of protection from bank erosion and sediment entering the channel, and those with vegetation alone, the least.

KEYWORDS

Channel stability, stream restoration, cost effectiveness, Great Barrier Reef

PRESENTER PROFILE

Dr. Andrew Simon is a Senior Consultant with *Cardno,* USA. He has 35 years of research experience in channel response of unstable channels, cohesive-soil erosion, streambank processes and modeling, and the role of vegetation. He is the author of more than 100 technical publications, and is the senior developer of the Bank-Stability and Toe-Erosion Model (BSTEM). Dr. Simon is a Special Professor in the School of Geography, University of Nottingham, UK.

1 INTRODUCTION

Failure to undertake quantitative analysis of bank-protection schemes typically increases the risk and uncertainty in design and often results in greater cost due to either "over design" or by having designs fail. The Bank Stability and Toe Erosion Model (BSTEM) is a fully deterministic simulation tool that has been used across a wide spectrum of environments to successfully predict streambank stability and to test the effectiveness of a broad range of mitigation schemes. The Dynamic version of the model with time-series flow data has been used in studies by Cardno, in the US, Australia and New Zealand, to assist in selection of appropriate mitigation techniques and to compare their cost-effectiveness. Mitigation techniques are aimed at either reducing the driving forces acting on the bank and/or increasing the forces resisting hydraulic erosion and bank collapse. Resisting forces such as critical shear stress, effective cohesion and friction angle are measured in situ in the field. For a recent flood-recovery study on the Burnett River conducted for the Burnett-Mary Regional Group (BMRG), Australia, simulations of different mitigation strategies included placing riprap at the bank toe, bank grading, re-vegetation, and construction of rock weirs or engineered log jams to deflect flows.

The Burnett River flows through the city of Bundaberg in its downstream reaches before exiting to Coral Sea and the Great Barrier Reef. The 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. 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.

2 METHODOLOGY

The geographic scope of this study extended from the mouth of the Burnett River east of Bundaberg, upstream to Eidsvold. In addition, the lower end of the Kolan River was included. These two reaches represent priority areas for investigation for the Burnett-Mary Regional Group (BMRG) to aid in their flood recovery efforts. BMRG selected eight sites along their study reach that were of interest for detailed investigation of current bank erosion rates, and potential mitigation measures that could be used to protect local assets. To investigate these eight sites in detail, field tests to quantify the geotechnical and hydraulic resistance of the bank and bank-toe materials were performed at each of the sites. Surveys of the banks were also carried out at each site to provide bank heights, angles, and stratigraphic layering for the tested bank. The data collected in the field were used to populate a Streambank Stability and Toe Erosion Model (BSTEM-Dynamic 2.0; Simon et al., 2000). These model results were used to calculate erosion rates for existing and mitigated conditions, which were then used in a cost-effectiveness analysis.

Simulations with BSTEM Dynamic were conducted for two non-mitigated cases to reduce uncertainty in model predictions and to provide a basis for simulating future erosion without mitigation (no action alternative). The first set of simulations was for the purpose of calibrating BSTEM between two known surveys. Because detailed surveys for two points in time were not available, top-bank edges from GIS-based air photos were used to determine the amount of bank retreat that occurred between the LIDAR data of 2009 and 2010 with the post-flood imagery shot in 2013. Mean-daily discharges from a nearby gauging station, adjusted for drainage area were used to establish the flow series encompassing the period bounded by the imagery. For the purposes of these simulations, the flow period used was 1 January 2009 to 31 July 2013. The amount of lateral retreat obtained from the imagery was then compared to the top-bank retreat predicted by BSTEM over the period. After successful calibration by iteration, the calibrated values were then applied to model potential future bank erosion under existing and mitigated conditions. For these model runs, BMRG and Cardno agreed to use a decade-long period to provide a meaningful comparison between erosion rates during wet and dry cycles. The period selected was slightly greater than 10 years and spanned 1 January 2003 to 31 July 2013.

2.1 ESTIMATING COST-EFFECTIVENESS OF MITIGATION MEASURES

Reducing land loss (bank retreat) and sediment loads from bank erosion can be accomplished in a number of different ways depending on the objective of the program and the resources available. Quantifying reductions from application of different mitigation strategies can then be designed accordingly. For example, to protect agricultural assets it is perhaps the reduction in bank retreat that is of paramount concern. In contrast, a better metric for protection of storage area above dams, and sediment delivery to the estuary and the Coral Sea might be reduction in volume or mass of sediment. Thus, modeling results were expressed not only in absolute values (m^3/m and m) but as a percent reduction in those parameters as compared to the 10-year, “no action” simulations. Cost effectiveness of each of the modeled mitigation measures was accounted for at each site based on (1) estimates of unit costs for materials and labor, and (2) the specific requirements (length, height and area) for implementation of specific design elements at each site.

2.2 MODELED BANK-EROSION MITIGATION SCENARIOS

Numerous combinations of bank treatments and protection schemes can be simulated within the BSTEM framework and all are related to how each scheme modifies the driving and/or resisting forces responsible for bank erosion. For example, placement of rock or large wood at the bank toe provides an increase in the resistance to hydraulic forces acting on the bank toe but does not address the hydraulic forces impinging on the toe or the shear strength of the overlying bank mass. Vegetative plantings, however, provide for not only an increase in the resistance to hydraulic forces but also additional root reinforcement to resist mass failures. Further, bank grading directly reduces the downslope, driving gravitational forces but does not alter resistance to hydraulic forces. Finally, bendway weirs or engineered log jams (ELJs) designed to keep the main flow thread away from the bank edge and re-direct it towards the center of the channel work to reduce the applied hydraulic forces acting on the bank toe and bank surface. These features do not modify either the gravitational, downslope forces or the shear strength of the in situ bank material. In general, alternative strategies that were simulated include various combinations of rock facing (at the bank toe and along the bank surface), riparian planting, grading of banks, and the use of Bendway weirs/ELJs. Table 1 provides a list of the mitigation alternatives tested, and the input parameters modified in BSTEM to account for each alternative.

Table 1 Mitigation measures tested and BSTEM input parameters modified to account for these measures. Note: ELJ = engineered log jam.

Mitigation Measure	**Modify critical shear stress of material**	**Modify soil shear strength to account for roots**	**Grade bank slope**	**Reduce applied shear stress acting on banks**
Rock at toe, no grading	✓			
Rock at toe and up bank	✓			
Additional riparian planting	✓	✓		
Rock at toe with riparian planting above	✓	✓		
Rock at toe with riparian planting and bank grading	✓	✓	✓	
Bendway weirs/ ELJs				✓
Bendway weirs/ ELJs, with rock toe				✓
Bendway weirs/ ELJs, with riparian planting		✓		✓

2.3 UNIT COSTS OF MITIGTION MEASURES

Cost effectiveness can be defined as the cost of implementing a particular mitigation measure per unit of sediment or bank saved. The effectiveness of each of the simulated mitigation strategies is, therefore, expressed herein, as a cost per unit volume of sediment-erosion reduction, and a cost per m of retreat reduced. To determine cost effectiveness, we must first be able to estimate the total cost of implementing a particular strategy. This is somewhat of a challenge without undertaking a detailed design and associated costing of each site. Reasonable estimates, however, may be obtained by applying the unit costs of materials and labor over the length, height and area covered by a particular alternative. Estimates of the required length of mitigation were estimated from inspection of the 2013 aerial photography for each main stem site. Consideration was given to the morphology of both the cross section and the reach. For example, if the site was located on an outside bend, it is prudent to protect not only the specific cross section but also the entrance and exit of the bend so as not to simply shift the instability to another part of the bend.

2.3.1 PROTECTION WITH ROCK

Rock is used in bank-protection schemes to resist hydraulic forces, typically at the toe of the bank to limit steepening and undercutting. The use of rock is generally combined with the placement of a filter fabric at the interface between the soil and the rock to limit winnowing of the finer materials. Rock is also used for the construction of weirs (flow deflectors) that extend into the flow field from the bank. In the case of a rock toe for example, one can cost the purchase, delivery and placement of rock per tonne of rock and then calculate the amount of rock required for a given height and length of protection. BMRG provided Cardno with an estimate of \$81.50/t for placed rock (I. Botha, written comm., 2013). The number of tonnes of rock required per meter of channel length varies according to whether it is placed against a vertical or sloping bank face (as in the case of toe protection) or it is placed on the channel bed (as in the case with a bendway weir). This is shown in Figure 1. By then applying the unit cost of \$81.50/t we develop a relation between the unit cost (per m of channel or weir) and the height of the rock protection (Figure 2).

Costs for toe protection with rock, often referred to as longitudinal stone-toe protection (LSTP) were based on the unit costs of rock provided by BMRG (\$81.50/t) and the red-colored equation shown in Figure 2, where cost is a function of the height protected. Estimated costs for each site, therefore, are based on the projected height of LSTP specific to the conditions and geometry of the site. For estimating costs for bendway (rock) weirs which are typically placed as a series of equally-spaced structures extending slightly upstream into the flow, guidelines developed the U.S. Federal Highway Administration (based on research by the U.S. Army Corps of Engineers) are used. The amount of rock is determined by the height, length, spacing and number of structures, which are in turn a function of the width of the channel, the length of the reach to be protected and the depth of mean, annual high water. As a more conservative approach and due to the apparent increase in the magnitude of peak-flow events in recent years in the study area, in this project the mean of the 11 highest daily flows (for each water year simulated) was used instead. Overall, as this is not an exercise in design but a means to estimate quantities of rock for approximate costing, the approach has been somewhat simplified. The following steps were used:

1. Determine the depth (d) of mean, annual high water;
2. Determine weir height (h) as 0.3d to 0.5d;
3. Calculate weir length (L) as ¼ of the channel width;
4. Calculate weir spacing (S) as 4 to 5 L;
5. Calculate the number of weirs using the length of the reach divided by S.
6. Calculate total cost by: First, determine the unit cost (per meter of weir length) for rock placement (of a given height) by the blue-colored equation in Figure 2; $\$cost = 259.93\ h^{1.9528}$. Then, multiply the result by weir length (L) and by the number of weirs.

2.3.2 PROTECTION WITH VEGETATION

Vegetation improves both the hydraulic and geotechnical resistance of banks as well as providing ecological benefits. Planting of the bank slope is generally combined with some kind of bank-toe protection with either rock or large wood. The cost of implementing a planting scheme is a combination of the cost of the plants and labor required for site preparation and planting. BMRG provided a unit cost of \$2.50/plant (I. Botha, written comm., 2013). Because of some uncertainty in the number of plants required in different settings, we have instead estimated a unit cost of \$5/m^2 based on previous experience.

2.3.3 PROTECTION BY GRADING THE BANKS

Grading of a bank slope reduces the gravitational, driving forces thereby increasing bank stability and is often combined with riparian plantings and bank-toe protection. This alternative requires the use of heavy equipment to perform cut and fill operations on the bank slope to batter it to an angle flatter then the friction angle of the material. The cost for mobilization and operation of the equipment can be variable due to location and accessibility, the height of the bank, access to the streambed, the amount of material to be moved per m of channel length, disposal of material. As such, the number of days required to perform the work can vary from several days to several months. We assume that four pieces of equipment would be required each day. They include a loader or bulldozer, an excavator or track hoe and two dump trucks. We further estimate an average, unit cost of $1,500 per day for each piece of equipment ($6,000/day total). We then estimate the number of days required to perform the work using an average of 2 days per 100 m of bank length. Given the estimated length of required mitigation at the sites, the time required for grading ranged from about 5 days to 24 days for the eight sites investigated in this study.

Figure 1 Tonnes of rock required relative to the height of the protected area for horizontal and vertical placement.

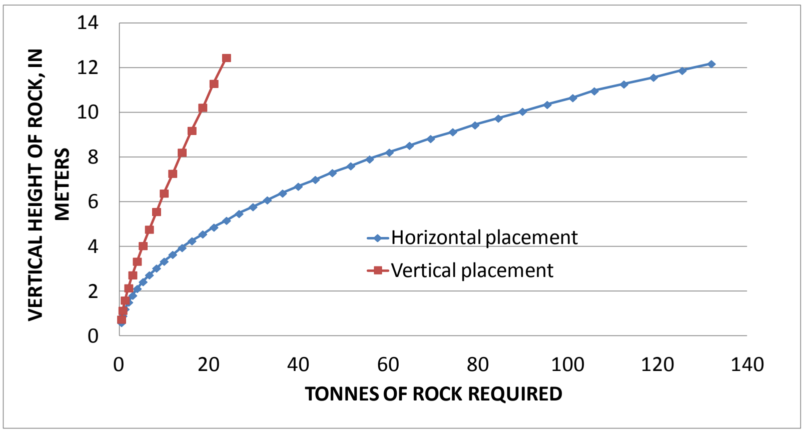
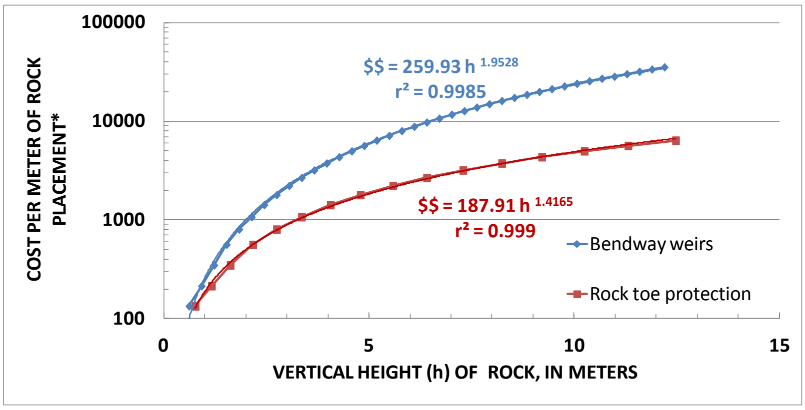


Figure 2 Estimate of the unit cost of rock placement (per meter of channel or weir length) as a function of the height of the protection. This does not include design costs and development of construction drawings.



2.3.4 PROTECTION BY LARGE-WOOD STRUCTURES

The use of large wood in bank-stabilization schemes is becoming more popular in many parts of the world, including Australia, because of the combined benefits to geomorphic and ecologic processes. The cost of wood structures such as engineered log jams (ELJs) can be quite variable and are often not reported in detail. Costs for construction of ELJs include the cost of the trees, delivery to the site and construction. Estimates of unit costs are done either per structure or per meter of channel length protected. Estimates per structure are also quite variable because of differences in the number and sizes of logs required for different types of ELJs. For example, a recent ELJ bank-stabilization project on the O'Connell River, QLD, Australia, used about 90 logs in each of three log-jam structures at a cost of $55,000 (about $18,000 per structure or about $275 per meter). Other wood structures may contain as few as three or four logs depending on the objective of the structure (fish habitat, bank stabilization, flow deflection etc.). For the type of bank protection envisioned for the Burnett River, we assumed that each structure would require from 20 to 80 logs.

Based on an extensive review of available cost information and review by Cardno design engineers, we calculated two average, unit costs for ELJ construction: $194/m of channel length protected and $ 19,050 per structure. Because of the great variability in ELJ project costs we also provide the 75th percentile of unit costs as: $280/m of channel length and $29,600 per structure. Most of this information was obtained from North American sources but costs from two Australian projects (one in Queensland and one in New South Wales) were also included. It should be stressed that the unit-cost estimates provided here and applied in the following sections of this report are just that, estimates. Additional uncertainty in cost estimates derived without full-scale design considerations may be related to:

- Difficult site conditions that may make placement more costly;
- Access to the streambed by heavy machinery;
- Vertical operational distance heavy machinery can operate from the bank top;
- Construction in wet (submerged) conditions;
- Differences in the cost of placing rock along a surface versus "keying" rock back into the bank at/or below bed level;
- Varying unit costs for rock of different sizes; and

The unit costs described above are used to estimate the total cost of a modeled mitigation alternative, which in most cases involves combinations of treatments .To obtain actual costs for implementation at a given site, the costs for detailed design drawings, computation of the types and amount of materials, and access by heavy machinery would need to be undertaken. Still, with the unit-cost estimates developed here, reasonable estimates of total costs and cost effectiveness for each site can be provided.

3 RESULTS

Results from the Shalom College site, which had the highest unit-erosion value, and largest bank retreat distance in the calibration runs, will be discussed here to provide an example of the way in which the BSTEM results were interpreted, and cost effectiveness analysis performed (Figure 3). The BSTEM results showed that without any remedial action at this site, an additional 52 m of retreat would occur over the next 10 years, with all of that occurring during the wet period and assocaited large peak-flow events. About 98% of the total unit-volume eroded (about 780 m^3) also occurred during the wet period, indicating that only 2% of the hydraulic erosion occurred during the drier period.

The relatively high-erosion rates seen at this site are the result of a high, bare bank composed of relatively weak materials that receives directed, accelerated flows due to a vegetated island in the reach. The result is that both moderate and high flows are deflected towards the bank toe, resulting in pervasive undercutting and representing an important process that would need to be addressed by mitigation. This interpretation is further supported by the results of the rock-toe and full-vegetation scenarios where, compared to the no action alternative of 783 m^3/m of erosion, 51.8 m^3/m and 353 m^3/m of erosion was predicted over the same period, respectively. Placed in terms of effectiveness in reducing the amount of sediment delivered, the rock toe (keyed into the bank) reduces erosion 93 % while established vegetation would reduce erosion at the site by 55 %. The other metric for determining effectiveness of these two (and other) alternatives is the potential reduction in lateral retreat. Although it is convenient to compare result in terms of percent reduction, it seems more meaningful in this case to compare absolute values. About 24 m of additional retreat is predicted for the full-bank vegetation case compared to about 4 m for the case with the rock toe. Two additional points about the comparison of these two alternatives need to be considered. First is the assumption that the planted vegetation will establish and not be killed or removed by flood or lack of water. This point emphasizes the potential need for maintenance and protection of any vegetative plantings, particularly in their first year. The second point is the difference in the cost of these alternatives, with the installation of a rock toe that is keyed into the bank being considerably more expensive.

Predicted bank retreat and resulting geometries for a range of mitigation alternatives at this site at the end of the simulation period are displayed in Figure 3. Analysis of the BSTEM results showed that geotechnical failures were responsible for the bulk of the material delivered to the river, but reductions in hydraulic bank erosion and steepening through toe protection, resulted in significant reductions in the quantity of material delivered by mass failures. This provides evidence of the type of actions (*ie.* some kind of toe protection) that would be appropriate at this site. Indeed, the model runs including rock placement on the bank face and/or toe, resulted in considerably greater reductions in both total eroded volumes, and bank retreat than those mitigation runs that involved only vegetation and/or grading. At this site, mitigation scenarios including bendway-weir structures, designed to deflect flow and reduce shear stresses applied to the banks, were also considerably more effective than vegetative plantings and/or grading. The height of rock required to successfully prevent bank toe erosion and subsequent bank over steepening from occurring depends on the shear stresses acting on different parts of the bank, which are controlled by channel slope, flow depth and channel roughness. For example, where vegetated islands force flow into a narrower section of the channel, flow depths will be greater for a given discharge, and the height of the bank that requires rock-reinforcement may, therefore, also be greater.

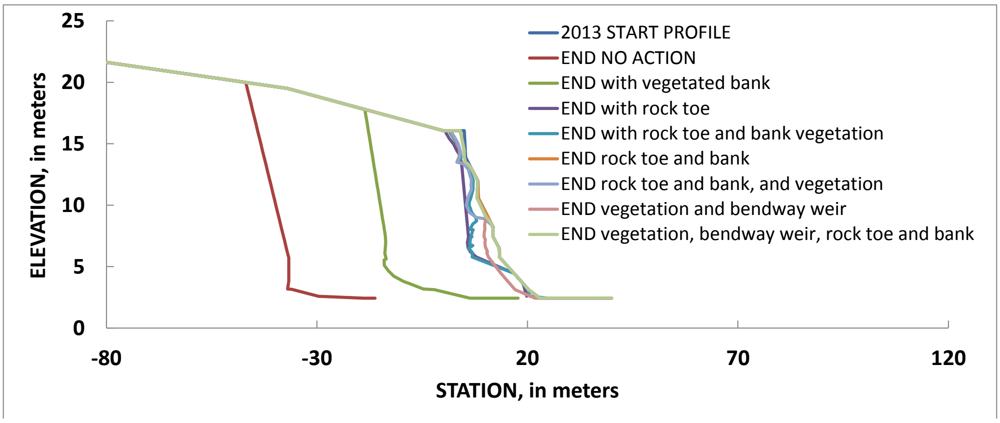
3.1 COST EFFECTIVENESS OF MITIGTOION SCENARIOS AT THE SHALOM COLLEGE SITE

As with any site, selecting a preferred alternative for the Shalom College site must be based on consideration of cost relative to an acceptable level of protection (magnitude of future land loss and likelihood of success). A summary of the estimated unit and total costs for the various mitigation alternatives at this site are shown in Table 2. The unit costs for mitigation scenarios involving vegetation and ELJs are considerably less ($66 to $260 per meter of bank length) than those requiring rock ($1,360 to $5,680 per meter of bank), whether it be for longitudinal stone toe protection, or for bendway weirs. Those mitigation runs that involve just vegetation and grading of the bank return relatively low costs per unit of sediment load or bank-top retreat saved, but they are also among the least effective measures in terms of total erosion reduction (Figure 4). Although the mitigation scenario that involves protecting the bank face and bank toe with rock (up to 11.1 m) resulted in the highest percent reduction in terms of sediment volume at this site, the cost for this scenario is the highest estimated (about $3,00,000). This scenario is likely to be cost prohibitive and was included only to represent an end-member case.

Considerably lower cost estimates were calculated for other effective mitigation strategies that had almost as much of a reduction in erosion and limiting bank-top retreat (Figure

4). For example, if we compare the percent reduction in erosion and bank retreat for each mitigation in Figure 4 (red and blue bars) with the total cost for that mitigation (green bars), we can see that installation of ELJs with additional vegetative plantings on the bank face and toe regions, provides a much more cost-effective alternative ($138,000), while still providing a similar result as the rocked bank face and bank-toe scenario. It should be noted that although the alternative combining ELJs with vegetation is much more cost effective, it also has a higher risk associated with it than the hard engineering solution of protecting parts of the bank with rock. This is because it will take time for vegetation to establish, and the structure will thus be prone to large floods until any new vegetation can root firmly enough to anchor itself in place. There may, therefore, be some additional costs associated with management and protection of vegetation as it establishes.

Figure 3 Top: photo of Shalom College site. Middle and bottom: Simulated, future bank retreat for the range of mitigation alternatives at the Shalom College site for the 10.6-year flow period used (2003-2013).


25
20
15
10
5
0
ELEVATION, in meters
-80
-30
20
70
120
STATION, in meters
2013 START PROFILE
END NO ACTION
END with vegetated bank
END with rock toe
END with rock toe and bank vegetation
END rock toe and bank
END rock toe and bank, and vegetation
END vegetation and bendway weir
END vegetation, bendway weir, rock toe and bank

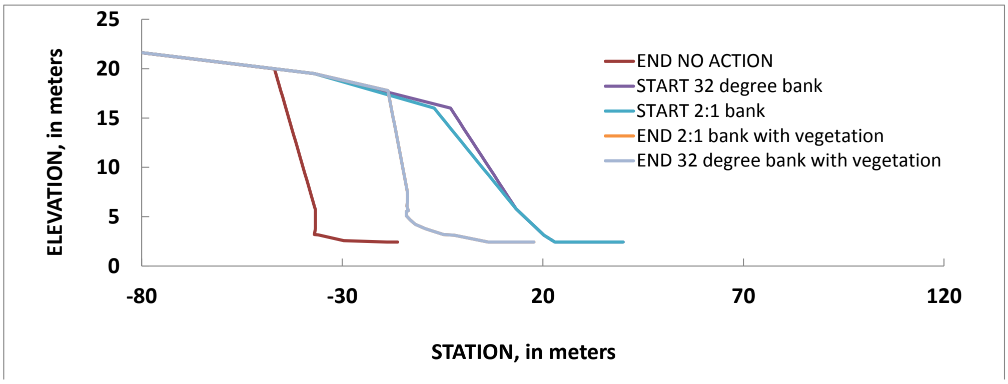

25
20
15
10
5
0
ELEVATION, in meters
-80
-30
20
70
120
STATION, in meters
END NO ACTION
START 32 degree bank
START 2:1 bank
END 2:1 bank with vegetation
END 32 degree bank with vegetation

Figure 4 *Plot showing percent reduction in sediment eroded at each site, and percent reduction in bank retreat, compared to the total cost for each mitigation scenario.*

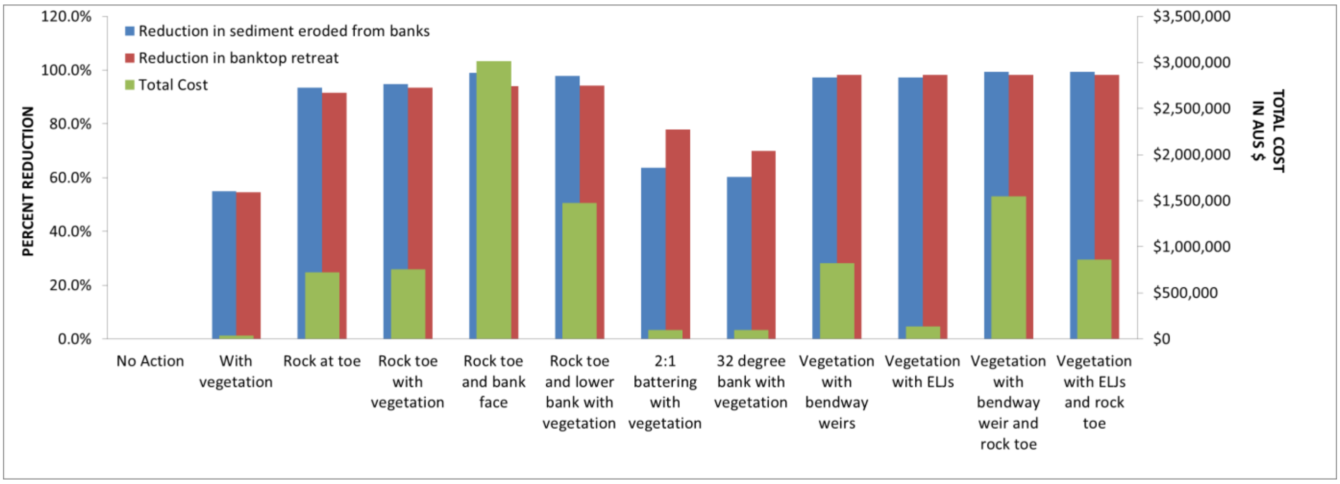


Table 2 Cost estimates for BMRG-03 for different mitigation scenarios, provided as total cost ($), costs by unit volume of sediment reduction ($/m^3), and per meter of bank retreat ($/m) prevented.

Scenario	**Protection**		**Unit Cost**	**Cost effectiveness**		
				Unit Cost		**Total Cost**
	Height	**Length**		**By volume**	**By retreat**	
	(m)	**(m)**	**($/m)**	**($/m^3)**	**($/m)**	**($)**
No Action	-	-	$0	$0	$0	$0
With vegetation	13.2	530	$ 66	$81	$1,230	$35,000
Rock at toe	4.1	530	$ 1,360	$988	$15,200	$722,000
Rock toe with vegetation	4.1	530	$ 1,430	$1,020	$15,600	$757,000
Rock toe and bank face	11.1	530	$ 5,680	$3,890	$61,600	$3,012,000
Rock toe and lower bank with vegetation	6.6	530	$ 2,790	$1,930	$30,200	$1,480,000
2:1 battering with vegetation	13.2	530	$ 186	$198	$2,440	$98,600
32 degree bank with vegetation	13.2	530	$ 186	$209	$2,710	$98,600
Vegetation with bendway weirs	13.2	530	$ 1,560	$1,080	$2,700	$824,000
Vegetation with ELJs	13.2	530	$ 260	$181	$30,300	$138,000
Vegetation with bendway weir and rock toe	13.2	530	$ 2,920	$1,990	$30,300	$1,550,000
Vegetation with ELJs and rock toe	4.1	530	$ 1,620	$1,110	$16,800	$860,000

4 CONCLUSIONS

The primary objective of this study was to provide a means of determining strategies for cost-effective protection of local assets in the context of flood recovery and system wide channel-stability concerns. Site-specific stability issues at eight locations were studied to better understand system wide trends, and investigate cost-effectiveness of potential mitigation measures at these priority sites. At-a-site investigations of unit-erosion rates (expressed in m^3/m of channel) were carried out using BSTEM, populated using geotechnical and hydraulic-erodibility data collected *in situ* at each of the sites. The BSTEM results for various mitigation scenarios at each site showed that at some of the sites, protection of the bank toe was the essential component in managing and reducing streambank erosion, and therefore, banktop retreat. In these cases, the most successful mitigation measures were protection of the entire toe using rock, with the addition of vegetation to the banks often further reducing bank erosion by protecting the upper bank from both hydraulic and geotechnical erosion. At some sites, however, the before and after geometries output from BSTEM indicated that even where the toe was protected, some erosion could occur above the protected zone. In these cases, mitigation strategies that focused on reducing shear stresses in the entire near-bank zone, rather than just protection of the toe, were found to be more successful in terms of erosion reduction and prevention of bank top retreat.

Cost estimates provided as part of this work served as an approximate guide for the mitigation scenarios presented. Overall, the scenarios involving rock in any form (rock toe or rock weirs) were the most expensive at any given site (costs vary according to rock size, and height of bank protected, but were an order of magnitude higher than other measures at most sites, typically ranging from \$1,000 to \$3,000 per meter of bank), and planting of vegetation was the least expensive (approximately \$5/m^2 of bank face or top). In general, however, mitigation runs including a rock component provided the greatest level of protection from bank erosion and sediment entering the channel, and those with vegetation alone, the least. It should also be noted, that the cost-effectiveness analysis showed that there are alternatives to the use of rock at some sites, with other combinations of mitigation strategies providing the same or only slightly less protection from future erosion. For example, the use of ELJs (with or without vegetation) often provided a good balance between bank protection and cost.

The results showed how the use of deterministic models, such as BSTEM can provide an effective way of quantifying the performance of proposed streambank stabilization measures. The balance between the cost-effectiveness of a given mitigation measure and the risk associated with the potential for ongoing erosion, and/or the failure of the implemented mitigation measure, must be considered on a site-by-site basis, according to available resources, the volume of sediment entering the channel, and the specific assets requiring protection. In the case of BMRG, final decision making depends not only on the total cost of each project, but also the asset protection afforded, and the volume of fine sediment that can be prevented from entering the river system, and ultimately reaching the Great Barrier Reef.

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