Rates of Bank Erosion under Different and Alternative-Flow Releases along the Mitta Mitta River: Developing Metrics to Limit Erosion Downstream from Dartmouth Dam

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Key Points

- Erosion rates modelled with BSTEM-Dynamic ranged from 0.9 to 9.8 m^3/m of channel length between 2006 and 2016.
- Erosion thresholds ranged from about 5,200 ML/d to almost 13,000ML/d.
- The magnitude and duration of flows above erosion thresholds exert strong influences on bank erosion rates and were used to develop metrics for operational guidance to limit erosion.
- Bulk-water transfers have the greatest potential to cause significant bank erosion because of high flow rates and durations above erosion thresholds.

Abstract

The Mitta Mitta River flows from Dartmouth Dam to the southern arm of Lake Hume and serves as a conduit for water transfers from Dartmouth Reservoir to the lake. Actual and prospective erosion of the banks under historical and alternative flow-release scenarios were modelled at seven sites along the Mitta Mitta River using the dynamic version of the Bank-Stability and Toe-Erosion Model (BSTEM-Dynamic). This approach allowed for identification of erosion-threshold conditions which ranged from about 5,200 megalitres per day (ML/d) to almost 13,000 ML/d, generally decreasing downstream. This coincided with a general increase in erosion rates downstream. Modelled bank-erosion rates over the period ranged from 0.89 m^3 per meter of channel length (m^3/m) to 9.8 m^3/m. Erosion did not begin at any site until daily-flow rates were greater than about 5,000 ML/d, indicating that this discharge would be a conservative, erosion-limiting daily-transfer rate. Previously reported recommendations for drawdown rates (5 mm/hr) were found to be slower than the hydraulic conductivity of any of the materials tested.

The magnitude and duration of flows above erosion thresholds exert a strong influence on bank erosion rates. Consequently, these parameters were evaluated for their relative influence on bank erosion during the 19 flow-release periods that occurred during the 2006-2016 period. Regression relations (with r^2-values greater than 0.9) show that that a metric, defined as the median ratio of the flows to the erosion threshold, times the duration of those flows (in days) explains much of the variation in average erosion rates for a given release type. Reversing these regressions can be used to help guide operational-release scenarios to limit bank erosion to a certain, acceptable value.

Keywords

Bank erosion, Mitta Mitta River, regulated flows, BSTEM-Dynamic

Introduction

The Mitta Mitta River flows for about 100 kilometers (km) downstream of Dartmouth Dam to the southern arm of Lake Hume (Figure 1). The river serves as a conduit for bulk-water transfers from Dartmouth Reservoir to Lake Hume for the primary purpose of ensuring that water supply in Lake Hume does not become too low, particularly during dry seasons. Completed in 1979, Dartmouth Dam has significantly altered the flow regime downriver by (1) storing inflows to pass of floodwaters over its spillway to mitigate floods downstream, and (2) provide bulk-water transfers during dry periods to supplement storage in Lake Hume. MDBA seeks to conduct water transfers to limit bank instability and environmental damage while promoting ecological attributes and ecosystem functions.

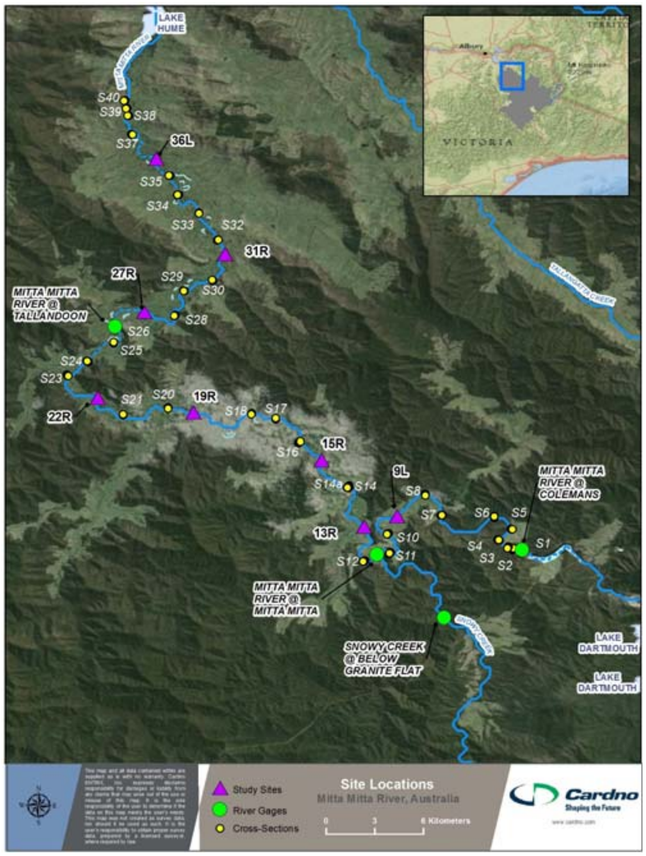


Figure 1. Map of the study reach showing locations of the detailed-study sites and flow gauges.

Bank erosion and lateral migration of meanders has long been an active process along reaches of the Mitta Mitta River. Bank scour, lateral-bank retreat and channel migration are the result of interactions between the hydraulic forces operating at the bank toe and other bank surfaces, and the gravitational (geotechnical) forces operating on the bank mass. MDBA wants a better quantitative understanding of the role of different operational-flow scenarios on bank processes and erosion rates. To quantify the important controls and threshold conditions on bank erosion along the Mitta Mitta River, this study takes a process-based approach to quantify the driving and resisting forces to use a deterministic numerical model: BSTEM-Dynamic.

This study addresses prior uncertainty regarding the role of the magnitude and duration of high-flow events on rates of bank erosion, particularly those flows between 5,000 and 10,000 ML/d. The frequency and duration of these flows have increased compared to pre-regulated conditions as a result of the bulk transfers to Lake Hume. Current practice is to keep releases below 5,000 ML/d where practical, taking into consideration demand patterns. Compounding this is the issue of the role of drawdown where there is conflicting evidence on the hydraulic conductivity of the banks. Green (1999) indicates that the banks can drain at rates of 0.7 metres per day (m/d), which would be sufficient to minimize large head differences between the ground and surface waters for rates of fall up to 0.35 m/d. A subsequent report (Lawson and Treloar, 2001), however, suggested that banks may drain at rates much slower (i.e., 0.086 m/d).

Objectives and Scope

This study provided for a physically based numerical analysis of bank-erosion processes along the Mitta Mitta River. The investigation focused particularly on determining the factors controlling bank-erosion rates along the Mitta Mitta River downstream from Dartmouth Dam. The primary objective was to determine the most effective way to make bulk transfers of water from Dartmouth Lake to Lake Hume that limits bank erosion. This meant investigating the roles of the magnitude and duration of high flows, rates of rise and particularly fall, and the general pattern of transfers in determining bank-erosion rates. This was accomplished by simulating bank erosion over a range of operational-flow scenarios using BSTEM-Dynamic at seven representative sites. The model provides for dynamic fluctuations of both ground and surface-water levels. Figure 1 shows a map of the study reach with locations of the detailed-study sites and flow gauges.

Boundary Resistance and Hydraulic Conductivity

The erodibility of surficial bank and bank-toe materials by hydraulic forces is important to modelling and predicting bank-erosion rates because it is the hydraulic processes that can cause undercutting of the bank, making it more susceptible to collapse. Based on 30 *in situ* tests with a submerged jet-test device, the hydraulic resistance (τ_c) of all but about 1% of the materials is equivalent to gravel-sized or finer materials (Figure 2, Right). In fact, about 50% of the materials are only as resistant as sand-sized materials $\tau_c \leq 2.0$ Pa.

Geotechnical data (cohesion and friction angle) obtained *in situ* with a Borehole Shear Tester are the fundamental measures of bank strength used to simulate and predict bank stability under a range of moisture conditions. Results of 13 individual tests along the Mitta Mitta showed that the cohesive strengths of the banks ranged from 0.0 to 13.9 kPa. The median value of effective cohesion is 0.84 kPa (average = 3.4 kPa), defining generally low strengths, in keeping with the generally silty and sandy bank materials.

Results of falling-head tests of hydraulic conductivity conducted in the field showed a median value of about 1.0 m/d, with an inter-quartile range from 0.4 to 2.3 m/d, indicating that these materials are generally quite conductive. These values should be considered relative to the maximum operational drawdown rates that range from 0.24 m/d (10 mm/h) to 0.48 m/d (20 mm/h) and to 0.7 m/d (30 mm/h), which are overlain in Figure 2 (Left). Thus about 55% of the materials tested drain faster than the maximum drawdown rates. These results further indicate that in some cases and at some sites, conductivity rates are less than recession rates and could, therefore, play a role in increasing bank erosion. Although Lawson and Treloar (2001) report infiltration rates “as low as” 0.086 m/d, the lowest rates measured in this study were 0.16 m/d at site 36L and 0.19 m/d at site 22R. For flows greater than 5,000 ML/d, they suggest drawdown rates should be < 0.12 m/d (5 mm/h) and possibly slower in the downstream reaches. This would be slower than any of the conductivity values measured in this study and would, therefore, certainly be effective at limiting the drawdown condition.

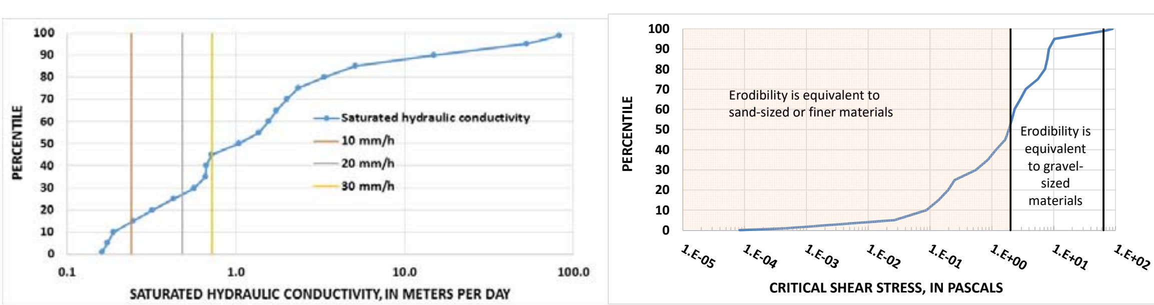


Figure 2. Distribution of measured, saturated hydraulic conductivity compared to the three entitlement

rates of fall (Left) and critical shear stress of the surficial bank materials (Right).

Hydrology

BSTEM relies on stage data to generate boundary shear-stress distributions along the wetted part of the bank face for each time step. Thus, a flow series for each of the seven modelling sites was generated from 15-minute discharge data from gauging stations on the Mitta Mitta River and Snowy Creek (Figure 1). These data were first converted to an hourly-maximum discharge record and then to an hourly-stage record using the Manning equation in a normal-depth calculation worksheet. The flow series for all of the Mitta Mitta River gauges reflect releases from Dartmouth Dam as can be seen from some of the broad peaks representing bulk transfers (Figure 3). The ratio of the catchment area at each site to the closest gauge was used to scale the flows.

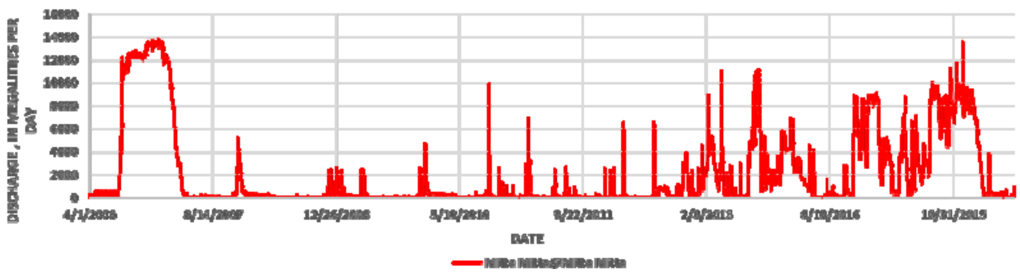
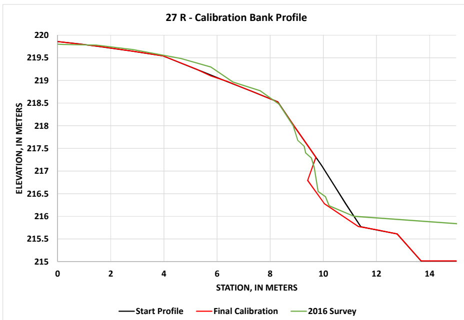


Figure 3. Maximum-hourly flows for a gauging station on the Mitta Mitta River system for the model period

Bank-Stability Modelling with BSTEM-Dynamic

BSTEM-Dynamic contains both geotechnical-stability and hydraulic-erosion algorithms, thereby allowing for deterministic analysis of bank stability over an unsteady flow series Simon et al. (2011). The time step and period of analysis is selected by the user. As such, flow stage at each time step is read into the model, and the amount and location of hydraulic erosion is calculated. The resulting new bank geometry for that time step is then used in the geotechnical algorithm to determine the stability of the bank by calculating the bank's Factor of Safety (<1.0 = unstable, >1.0 = stable) at that time step. If a geotechnical failure is predicted, the geometry is updated again to account for the failure before the next flow-stage value is read in at the next time step. In this way BSTEM-Dynamic 2.3 can predict the retreat of a streambank for flow series ranging in length from hours to decades. In addition to being able to account both hydraulic and geotechnical processes, the model has a groundwater component that contributes to the geotechnical-strength algorithm, and can account for the effects of root-reinforcement provided by riparian vegetation, through the RipRoot sub-model.

To calibrate the model for a site, the 2006 geometry, hourly-flow series and the bank-resistance data for each identified layer were input into BSTEM-Dynamic. In addition, a hydraulic roughness value (n) was assigned to each layer according to the characteristics of the bank surface. The model was then run for the full simulation period until completion (1 April 2006 to 6 July 2016). An example is shown for site 27R (Figure 4, Left). Results of the calibration runs showed bank-erosion volumes ranging over an order of magnitude from about 0.89 m^3/m (of channel length) at site 27R to about 9.8 m^3/m at site 22R (Figure 4, Right). In general, the largest amount of erosion occurs in the middle reach at sites 19R and 22R with sites (9L, 13R and 27R) having the lowest amounts. Because each of the sites was subjected to the same flow series, differences in bank-erosion rates at individual sites are related to site-specific conditions at that site, including bank height and angle, bank-material strength and, particularly, bank-surface erodibility. This is because in spite of moderate bank-material strengths, a location that has weak bank-toe materials and is subject to scour and undercutting during moderate and high flows can readily lose support for the upper part of the bank and fail. The two sites with the highest amount of erosion over the period, sites 22R and 19R, have the most erodible bank-toe materials, with critical shear stresses of 0.8 and 1.1 Pa, respectively (equivalent to sand-sized materials).



Site	Geotechnical Erosion (m^3/m)	Hydraulic Erosion (m^3/m)	Total Erosion (m^3/m)	Unit Erosion ($m^3/m/y$)
9L	-	0.978	0.978	0.095
13R	0.149	0.771	0.920	0.090
15R	0.379	1.23	1.61	0.156
19R	0.171	3.48	3.65	0.355
22R	6.25	3.57	9.82	0.957
27R	0.076	0.812	0.888	0.087
36L	0.181	0.978	1.16	0.113

Figure 4 – Calibration results for site 27R (Left) and for all sites (Right);

Bank Erosion during Flow Transfers and Flow-Threshold Conditions

The relation between flow-transfer periods and bank erosion can be obtained by taking the results from the BSTEM output and summing the hourly bank-erosion data that fall within a given flow-transfer period. This, along with quantifying the actual flow thresholds that initiate erosion, helps provide insight into the pattern of alternative flow scenarios to test which would tend to limit bank erosion. Thus, analyses were conducted to: (1) evaluate any relation between bank erosion and the magnitude and duration of flow events that occurred during the period April 2006 to July 2016; and (2) determine the flow-thresholds for bank erosion.

Erosion amounts during the 19 flow-transfers periods were extracted from the model results and processed to determine the total amount of erosion, transfer amount and duration of the transfer (Figure 5). Aside from two relatively low average monthly release periods of 2,763 and 8,470 ML/mo, measurable erosion has occurred at average monthly- transfer rates above 90,000 ML/mo. Total-erosion amounts (sum of erosion at each site) increased for the average monthly bulk-transfer amounts of 131,000 (20 months between August 2014 and March 2016) and 244,000 ML/mo (9 months between August 2006 and April 2007). These represent the three bulk-transfer periods with the greatest average-monthly flows between 2006 and 2016. These flow periods with the highest erosion amounts also have the longest durations, ranging from 9 to 20 months.

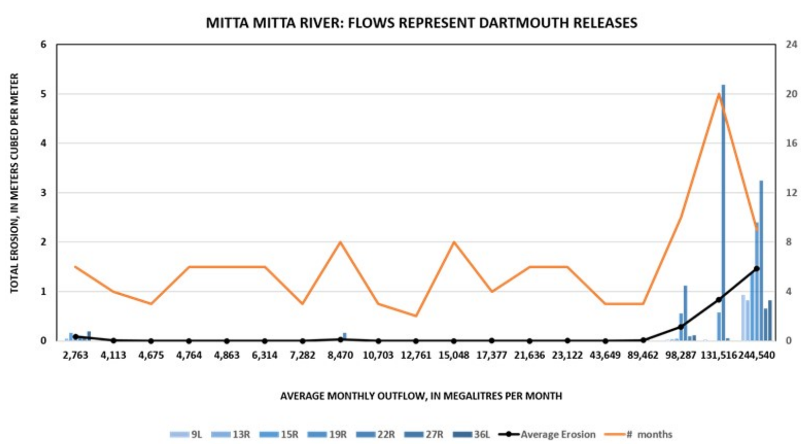


Figure 5 – Bank erosion during flow-transfer periods also showing durations of transfers.

Clear operational guidance based on average-monthly values and duration of the flow periods is not appropriate because of the uncertainty surrounding the magnitude of the daily flows represented by a particular average value. To address this, we need to include the resistance of the boundary to quantify the magnitude and duration of flows that exceed that critical condition. For instance, sites with the most erodible materials having the lowest thresholds for erosion. Based on BSTEM output, the three sites with erosion thresholds near 5,000 ML/d (19R, 22R and 36L) have the three lowest critical shear stress values at the bank toe; 1.1, 0.8 and 0.1 Pa, respectively, equivalent to the resistance of sand-sized materials. The sites in the upper part of the study reach (sites 9L, 13R and 15R) have the highest erosion thresholds, ranging from about 9,500 ML/d at 9L to 13,000 ML/d at 13R (Table 1). From this we would expect that the upper sites will show less erosion between 5,000 and 10,000 ML/d with erosion increasing closer to the 10,000 ML/d threshold.

Table 1. Erosion-threshold values for each of the seven modelled detailed-study sites.

Site	9L	13R	15R	19R	22R	27R	36L
Threshold (ML/d)	9,504	12,960	11,232	5,184	5,184	6,912	5,702

The percent contribution of different discharge classes is compared to contributions expressed as actual volumes of erosion (Figure 6). The left plot places all sites on an equal footing by expressing results as relative contributions, clear differences in the amount of bank erosion at sites 22R and 15R, or 22R are apparent. Site 22R is shown to be most responsive at lower flows with the bulk of erosion taking place in the range of 6,000 to 10,000 ML/d. The two downstream-most sites (36L and 27R) are also quite responsive at moderate flows, resulting in the bulk of the erosion occurring at about 10,000 ML/d. Aside from site 22R, measureable erosion does not take place until flows of about 10,000 ML/d are being discharged.

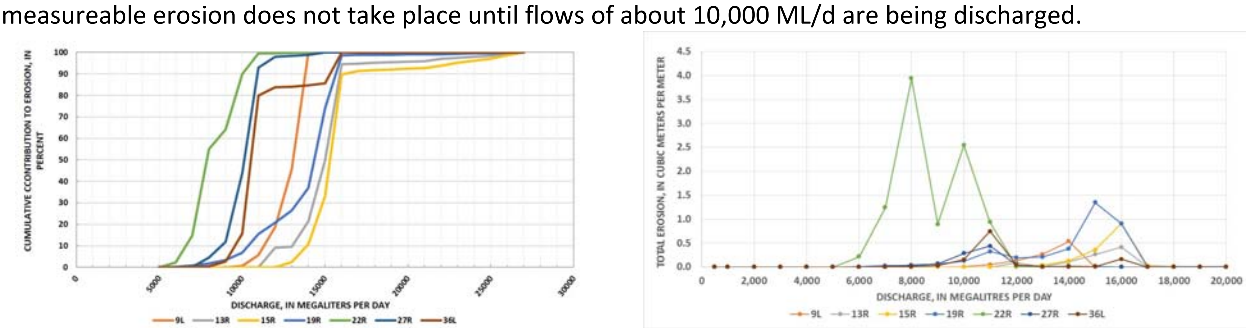


Figure 6. Contribution of discharges to bank erosion. Note the lack of erosion below 5,000 ML/d.

Bank-Erosion under Alternative Flow Scenarios and Metrics for Operational Guidance

To help determine the most effective way to make bulk transfers of water from Dartmouth Dam downstream to Lake Hume without causing undue environmental damage, a series of alternative-flow scenarios was developed. The basis for the flow scenarios as provided by MDBA was that all of the scenarios would deliver about the same amount (volume) of water over a similar period. Obviously, there is a myriad of potential combinations of these variables that could be tested. Four were selected that deliver about 920,000 ML in a 7-month period (~130,000 Gl/month averaged over 7 months) (Figure 7).

1. *Moderate - Constant* **–** This flow scenario represents a “constant” release of 5,000ML/d over the entire flow period excluding the time to peak and for recession to 200 ML/d.
2. *Maximum RoF* – The second scenario represents a variable release strategy to approximate a naturally-shaped hydrograph. This scenario uses the maximum permissible RoF of river levels at the Colemans gauge (20 mm/h), the 2nd-highest peak-flow rate of about 7,500 ML/d and the 2nd-shortest duration of peak flows at 30.3 days.

3. *Slower and Smaller* – this scenario is similar to the second, with a variable release except that rates of fall are kept to 5 mm/h, and peak-flow rates are about 6,400 ML/d. The duration of peaks for this scenario is also the shortest, at 25.8 days.
4. *Worst Case / Maximum Flow* – transfers are undertaken as late as possible and at channel capacity rates of approximately 10,000 ML/d. Here a single peak is held for 85.5 days. This was a feature of past operations and such flow patterns were known to exacerbate bank erosion.

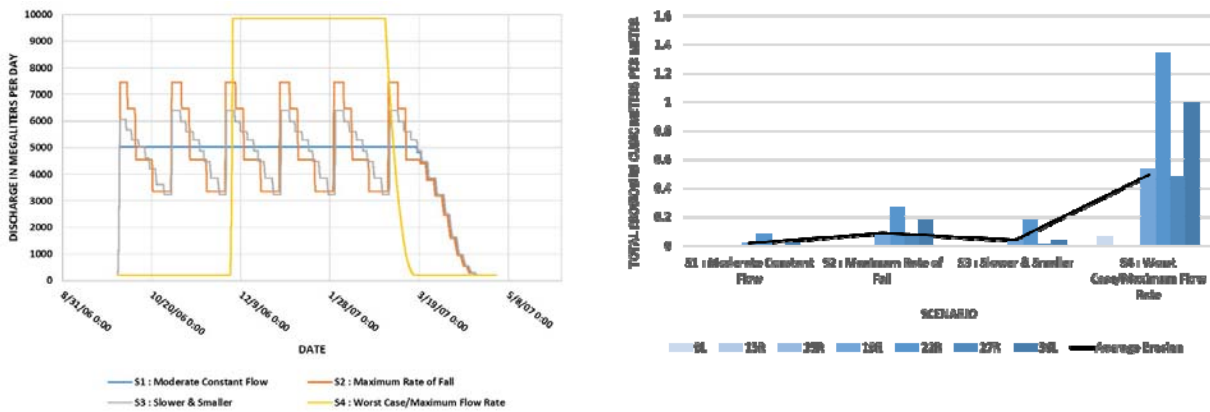


Figure 7. Hydrographs of the four alternative-flow scenarios (Left) and associated bank-erosion (Right).

Erosion rates varied by flow scenario (Figure 7). From lowest erosion rates to highest they are (with average values in parentheses):
1. Moderate-Constant Flow (0.016 m^3/m);
2. Slower and Smaller (0.037 m^3/m);
3. Maximum RoF (0.086 m^3/m); and
4. Worst Case / Maximum Flow Rate (0.488 m^3/m).

The Worst Case / Maximum Flow represents the scenario with the highest erosion rates at the sites that had any erosion (Figure 7, Right). This should not be surprising given that this flow scenario has the highest peak flows (about 10,000 ML/d), and the highest magnitudes and durations of flows in excess of threshold conditions (38-51%). At the other end of the spectrum is the Moderate-Constant Flow scenario where we get the lowest erosion rates for all sites with any erosion. This was also to be expected because in spite of the fact that the duration of the peak flow (167 days) was almost twice that of the Worst Case scenario, the peak-flow rate was held to about 5,000 ML/d and only 6% to 11% of the flows were in excess of the threshold flow condition. It should be noted, however, that although this the constant-flow scenario produces minimal erosion because it is below erosion-threshold values for all sites, it could produce negative environmental and ecological aspects because of the lack of flow variability. It is unlikely that operational guidelines to limit bank erosion would be developed in isolation of these issues.

A series of relationships using the magnitude and duration of flows above the erosion threshold as the primary metric, were developed. These are useful in interpreting how the same sites respond differently to the different alternative-release schemes as a function of the magnitude and duration of flows. Lack of space here precludes a detailed discussion of their development and the reader is directed to the major Cardno report for MDBA which this is based (Simon et al., 2018). Here we refer to one that is based on the sum of the ratios of the flow rate to the threshold value for each day that it is in excess of the erosion threshold (Figure 8). In effect, this single value then represents both magnitude and duration for each site/scenario. From this we can see that the Constant-Moderate Flow (Scenario 1) can withstand long durations above the erosion threshold because the magnitude of those excess flows is small. The converse is true for the Worst Case / Maximum flow (Scenario 4) scenario where greater flow magnitudes result in shorter acceptable flow durations to limit bank erosion. The Maximum RoF (Scenario 2) also shows a clear and similar increase in bank-erosion rates with increasing duration. For the Smaller and Slower (Scenario 3), bank-erosion rates don't increase appreciably until the index is greater than about 125.

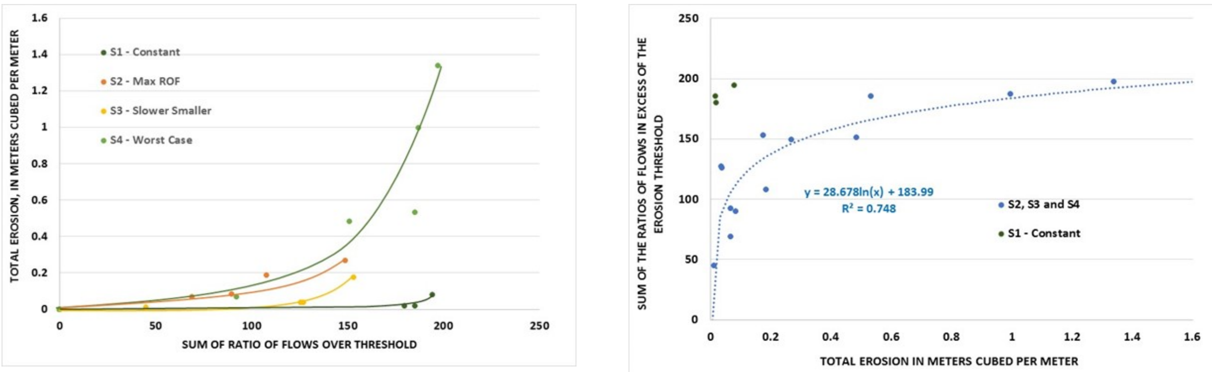


Figure 10. Relations between bank-erosion rates and the sum of the daily ratios of flow-to-erosion threshold over the 216-day simulation period for each flow scenario (Left) and inverted for flow scenarios 2, 3 and 4, which capable of producing significant erosion (Right). The regression equation shown on the right graph can be used to estimate the magnitude and duration of releases that produce certain bank-erosion rates.

As a potential tool for operations managers, the data in Figure 8 (Left) are combined for those flow scenarios that are capable of producing significant erosion (Scenarios 2, 3 and 4) and inverted to solve for the sum of these ratios (Figure 10, Right). Results, which can be easily derived for a proposed flow release, are listed for specified erosion rates:

- 0.05 m^3/m, 98.1; 0.10 m^3/m, 118.0; 0.15 m^3/m, 129.6; 0.20 m^3/m, 137.8;
- 0.30 m^3/m, 149.5; 0.40 m^3/m, 157.7; and 0.50 m^3/m, 164.1.

Summary

Using hourly time steps, a historical flow period from 2006 to 2016 was selected for modelling to coincide with the timing of repeat channel surveys. Changes in bank geometry over the period were used to calibrate BSTEM-Dynamic. Erosion rates ranged over an order of magnitude, from 0.89 m3/m (of channel length) at site 27R to 9.8 m3/m at site 22R, located on the outside of a broad meander bend. This deterministic approach allowed for identification of specific erosion-threshold conditions, which ranged from about 5,200 ML/d to almost 13,000 ML/d depending on the resistance of the bank materials and the geometry of the bank. The highest erosion thresholds and, therefore, lowest bank-erosion rates were found in the upstream reaches at sites 13R, 15R and 9L. In general, erosion increased downstream. At all sites, erosion did not begin until daily-flow rates were greater than about 5,200 ML/d, indicating that this discharge would be a conservative, erosion-limiting rate for transferring water.

Field measurements of hydraulic conductivity of the banks disclosed a median value of about 1.0 m/d (~40 mm/h) and an inter-quartile range from 0.4 to 2.3 m/d (17 to 95 mm/h), indicating that the bank materials are generally quite conductive. These values are generally higher than operational drawdown rates, indicating that water can normally drain out of the banks at the rate of recession imposed by releases. Limiting drawdown rates to half or less of the measured conductivity (i.e., below 15 mm/h, to as low as 5 mm/h) would provide even greater certainty to limit drawdown-associated bank instability.

The Worst Case / Maximum Flow scenario represents the case with the highest erosion rates. This is not surprising, given that this flow scenario has the highest peak flows (about 10,000 ML/d) and the highest magnitudes and durations of flows in excess of threshold conditions. In contrast, the Moderate-Constant Flow scenario had the lowest erosion rates. This too was to be expected because the peak-flow rate was held to about 5,000 ML/d, below the erosion threshold for most sites. Although the Moderate-Constant Flow scenario produces minimal erosion, it could produce other negative environmental and ecological impacts because of an unnatural lack of flow variability. Further, except for site 22R, measurable erosion starts to occur at about 10,000 ML/d, indicating that this may be an important discharge management threshold. Thus, flows between 5,000 and 10,000 ML/d, which produce some erosion, may represent a reasonable range of daily-transfer rates while maintaining general bank stability. This of course is a function of the local erosion thresholds and the duration of the flows above threshold. Establishing various combinations of magnitude and duration that result in acceptable amounts of erosion within this flow range can be estimated using regression relations that were developed from the simulated erosion rates and these flow parameters.

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