Full Paper

Rates of Bank Erosion under Natural and Regulated Flows in the Upper Murray River System: Khancoban Dam to Jingellic

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Key Points

- Regulation has caused important changes in the hydrologic regime of the Swampy Plain and Upper Murray Rivers in the reaches closest to Khancoban Dam.
- Field data on resistance of the banks was used in combination with BSTEM-Dynamic to simulate bank erosion for unregulated and regulated conditions using a 32-year time series of hourly flows.
- Regulation has led to changes in bank-erosion rates with increases in the reaches closest to the dam and decreases in the reaches farthest downstream, the former related to greater flow durations that exceed erosion thresholds

Abstract

The Snowy Mountains Scheme provides for inter-basin transfers of water and for hydro-electric power generation in the upper reaches of the Murray River System. Since 1966, the magnitude, frequency and duration of discharges in the Swampy Plain and Upper Murray Rivers have been modified by the Scheme. Increases in mean-annual flows following regulation were determined to be 127% in the upstream-most reach on the Swampy Plain River, 68% above the confluence with the Tooma River and 16-19% downstream at Jingellic. The duration of half-capacity and channel-capacity flows at Khancoban showed increases from 19 to 97 days and unchanged at about 3 days, respectively. Downstream at Jingellic, there was no change.

The hydraulic and geotechnical resistance of the banks was determined *in situ* at eight sites along the reach and disclosed relatively weak and erodible bank sediments. These data were used in the dynamic version of the Bank-Stability and Toe-Erosion Model (BSEM-Dynamic) to predict bank erosion under regulated and un-regulated conditions at hourly time steps for a 32-year period. The greatest difference between bank-erosion rates under un-regulated and regulated flows is in the reach closest to Khancoban Dam (increase of 255%). Differences in total unit-erosion along the study reach tend to decrease moving away from Khancoban Dam, becoming negligible below the Tooma confluence. In the downstream-most reaches, bank-erosion rates are lower than for un-regulated flow conditions. The majority of the other sites show a 22-129% increase in total erosion between the un-regulated and regulated flow series, largely attributable to the increased duration of flows above the erosion thresholds.

Keywords

Bank erosion, Upper Murray River, regulated flows,

Introduction and Scope

The Swampy Plain River flows for about 11 km from the downstream side of Khancoban Dam to its confluence with the Upper Murray River just upstream of the gauge at Bringenbrong. From this point, the Upper Murray River flows for about 82 km to the "Full Supply Level" of Lake Hume (about 18 km below Jingellic). Bank erosion and lateral migration of meanders has long been an active process along reaches of the Upper Murray River that pre-dates river regulation. Historically, these rivers have migrated across their floodplains and the valley is filled with examples of this activity including cut-offs, oxbows and paleo-channels. Within the catchment, the magnitude, frequency and durations of discharges have been modified due to the Snowy Mountains Scheme. The regulation of the Tooma River commenced in 1961 and the Swampy Plain River in 1966, with all works being complete by 1970. In the Upper Murray River System, the general intensity and impact of these imposed changes to the flow regime on the river channel would be expected to decrease downstream from Khancoban Dam as "natural" flows from other parts of the catchment mix with the regulated flows discharging from the Swampy Plain River. The magnitude of channel adjustments would also be expected to decrease with time from the initiation of the altered hydrologic regime. Still, the lack of a quantitative understanding of the hydraulic and geotechnical processes acting on the banks has made it difficult for Snowy Hydro to evaluate the role of regulated flows on bank processes and erosion rates. Eight representative, detailed-study sites were selected for data collection and modelling. (Figure 1). The primary objective of this study was to determine the controlling factors and differences in bank-erosion rates between pre-regulation and regulated flows in the Swampy Plain and Upper Murray Rivers downstream from Khancoban Dam. Secondary objectives were to quantify the extent of bank failures along the reach and to determine the effectiveness and cost effectiveness of a range of mitigation strategies.

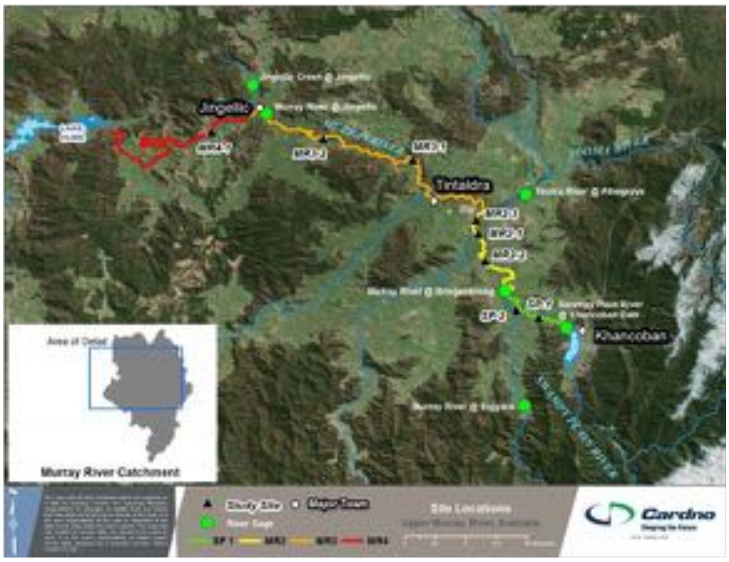


Figure 1. Map of the study reach showing locations of the four sub-reaches, detailed-study sites and flow gauges.

Hydrology

In an effort to view differences in the un-regulated and regulated flows calculated in this study with results from previous investigations, mean-daily data were used. We have seen that the changes in mean-daily flows for the post-regulation period at Jingellic (which is about 76 km downstream from Khancoban Dam), are about 16% for the period 1891 to 2015, inclusive. Results for mean-annual flows are similar. Earlier estimates, where pre-regulation flows are based on the results of hydrologic modelling by Gippel et al. (2000) show a 22% increase in mean-annual flows at Jingellic for the 1970-1998 post-dam period. Their analysis of mean-annual flows closer to Khancoban Dam show greater differences between un-regulated and regulated flows;

127% increase along the Swampy Plain River and 72% increase along the Murray River above the Tooma confluence which is similar to the findings of this study.

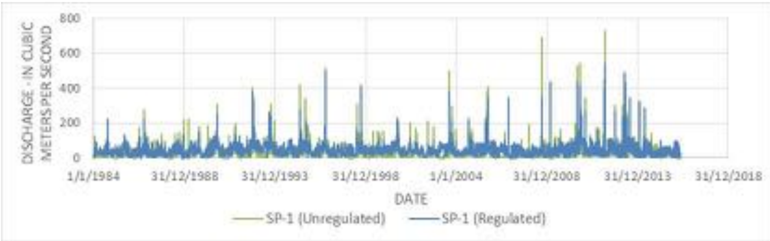
Based on the un-regulated flow series derived from the data provided by Snowy Hydro and the regulated flows obtained from gauge data for the Swampy Plain River and the Murray River at Bringenbrong, specifics of the altered flow regime were examined. As expected, differences were greater along the Swampy Plain River than in the Upper Murray River at Bringenbrong, but at both sites mean-daily flows were increased across the entire flow regime except for the very highest discharges. The decrease in peak-flow values (0.1th exceedance percentile) were similar for the two locations and relatively small in magnitude, -14% and -12% for Khancoban and Bringenbrong, respectively. Decreases in the highest peaks (0.01th exceedance percentile) were about -20% and -35%, respectively. In contrast, sizeable increases were noted for the 10th percentile (79% and 32%). Increases for the low and moderate discharges were substantial (Table 1).

Table 1. Summary of differences in 1984-2016 unregulated and regulated, mean-daily flows as calculated for the Swampy Plain River at Khancoban and Murray River at Bringenbrong and scaled downstream. Data for the Murray River at Jingellic are derived from gauge values.

Gauge	Exceedance	Unregulated	Regulated	Difference	
	(%)	m^3/s			(%)
Khancoban	0.01	390	310	-79.3	-20.3
	10	43.8	78.6	34.8	79.4
	50	12.0	40.3	28.3	235
	90	3.5	13.0	9.5	274
Bringenbrong	0.01	674	435	-239	-35.5
	10	80.2	106	25.8	32.1
	50	22.9	53.9	30.9	135
	90	7.1	20.4	13.2	185
Jingellic[1]	0.01	1212	1259	46.9	3.9
	10	179	179	-0.3	-0.2
	50	46.4	67.0	20.6	44.3
	90	13.3	22.5	9.2	69.7

Flow series representing both unregulated and regulated conditions for the 1984-2016 period needed to be derived. Unregulated flows (referred to as pre-SMA flows by Snowy Hydro) emanating from Khancoban Dam were developed by Snowy Hydro for use by Cardno. These were based on an empirical formulation that relied on the discharges measured at other locations upstream of the impoundment, adjusted for travel time and multiplied by known inflow factors. These hourly flows were then scaled downstream along the Swampy Plain River according to increases in catchment area. Flows from the unregulated Upper Murray River were then added to the reach below the confluence based on discharges from the gauge at Biggara, scaled to the confluence location. Adjustments for travel time were based on an analysis of the timing of peaks between Bringenbrong and Jingellic. An example of the two flow series is provided in Figure 2.

The last step in preparing the hydrologic data for bank-stability modelling was to convert the scaled hourly-discharge data into an hourly-stage record by establishing a stage-discharge relation for each site. This was accomplished by solving the Manning equation in a normal-depth calculation worksheet using the site-specific flow series with the 1996 or 2016 surveyed cross section and the bed slope for each site. Calculations were made for a range *n*-values, with the appropriate *n*-value selected based on field conditions.



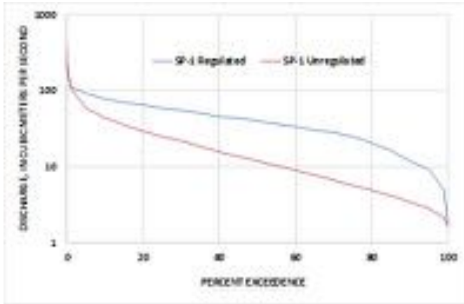


Figure 2. Unregulated and regulated time series for the upstream-most site on the Swampy Plain River (Left) and comparison of differences in the two flow-frequency curves (Right).

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.

Threshold and Other Flows Contributing to Bank Erosion

Analysis of the BSTEM-Dynamic output allows us to investigate which flows are capable of eroding the bank toe and bank face and, therefore, responsible for total bank erosion. The discharge (or range of discharges) where erosion is initiated is referred to here as the threshold discharge. An example is shown from site MR2-1 (Figure 2) where erosion starts at flows of about 105 m^3/s. The threshold discharge is of course just a metric for the hydraulic conditions that occur at the point of incipient motion and reflects the resistance of the generally weak boundary materials (Figure 3). A low erosion threshold at site SP-1 (26 m^3/s) leads to considerable erosion. This flow rate was exceeded about 25% of the time under unregulated conditions and about 75% of the time under regulated conditions. Recall that increases in flow in the SP1 reach just downstream from Khancoban Dam are the greatest of any of the reaches. Erosion thresholds and the associated flow-exceedance values are shown in Table 2.

Table 2. Erosion-threshold values for each of the eight detailed-study sites.

Site	SP-1	SP-2	MR2-2	MR2-1	MR2-3	MR3-1	MR3-2	MR4-1
Erosion threshold (m^3/s)	26	95	58	105	97	160	210	164
Unregulated-flow exceedance (%)	25	1-5	20	5	15	10	5	10-15
Regulated-flow exceedance (%)	75	5	45	10	35	10	5	15
Catchment area (km^2)	802	884	2,385	2,395	3,403	6,261	6,434	7,158
Discharge/unit area (m^3/s per km^2)	0.03	0.11	0.02	0.04	0.03	0.03	0.03	0.02

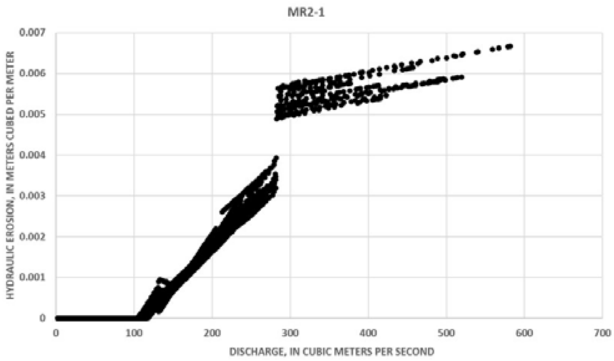


Figure 2. Example analysis of the flows responsible for erosion at site MR2-1. Here, the erosion threshold is about 105 m^3/s, exceeded about 10% of the time under regulated conditions.

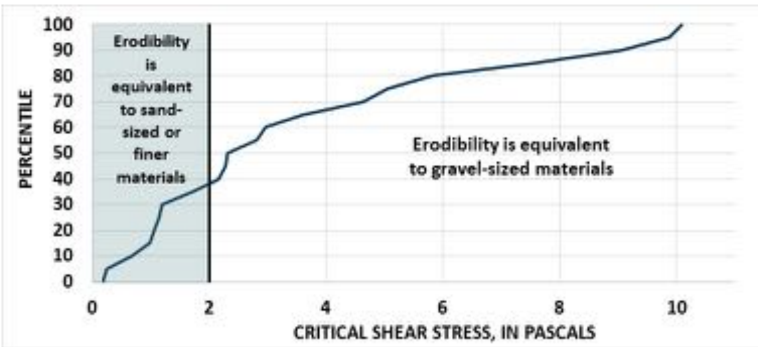


Figure 3. Distribution of critical shear stress and equivalent diameters showing relatively erodible bank materials.

Bank-Erosion for Unregulated and Regulated Flows: 1984-2016

To assess the impact of the regulated flow regime on bank-erosion rates, BSTEM-Dynamic simulations were conducted at each of the detailed-study sites for both an hourly regulated-flow series and the calculated, hourly unregulated-flow series. The simulation period was 1 January 1984 to 30 April 2016. Differences in erosion rates between these two flow scenarios represent changes due to flow regulation.

Modelling results showed that bank erosion occurred at all sites under both regulated and un-regulated flow conditions. Results were highly variable between locations and reflect the relative changes in the hydrologic regime, stock access and the presence of protection measures (Table 3). Differences in the rates of bank erosion under regulated conditions compared to un-regulated, range from a reduction of about 68% at MR4-1 (the most downstream site) to an increase of 255% at SP-1 (the most upstream site). One of the first things to note is that under the unregulated flows, the trend in total erosion is to generally increase as you move downstream from Khancoban Dam (Figure 4, Left). Under the regulated flow regime, however, the greatest amount of erosion occurs at the upstream-most site (SP-1).

Differences in total unit-erosion under regulated conditions along the study reach tended to decrease as you moved downstream from Khancoban Dam (Figure 4), becoming negligible at site MR3-1 and actually becoming less than for un-regulated conditions at MR3-2 and MR4-1. This is in keeping with the general decrease in the impact of flow regulation away from the dam. The sites in Reach 2 show a 22-129% increase in total erosion between the regulated and un-regulated flow series. Site MR4-1 responds differently from the other sites, as it shows a significant decrease in erosion under the regulated flow series. Although this might seem surprising given the increase in flow magnitudes across the middle part of the flow regime, the discharge range of these increases is, for the most part, below the erosion threshold of 164 m^3/s for the site.

Table 3. Summary of bank-erosion totals predicted by BSTEM-Dynamic for the regulated and unregulated flow period: 1984-2016. Note: * = very-low erosion rates at this site makes estimate of percent reduction unreliable.

Site	Regulated Flows				Unregulated Flows				Difference in Unit Erosion Rates (regulated - unregulated)	
	Geotechnical erosion (m^3/m)	Hydraulic erosion (m^3/m)	Total erosion (m^3/m)	Unit erosion ($m^3/m/y$)	Geotechnical erosion (m^3/m)	Hydraulic erosion (m^3/m)	Total erosion (m^3/m)	Unit erosion ($m^3/m/y$)	($m^3/m/y$)	(%)
SP-1	28.9	20.6	**49.5**	**1.53**	4.25	9.71	**14.0**	**0.43**	1.10	**255**
SP-2	1.24	1.84	**3.08**	**0.10**	1.65	2.59	**4.24**	**0.13**	-0.04	**-27.5***
MR2-2	11.6	7.70	**19.3**	**0.60**	9.57	6.23	**15.8**	**0.49**	0.11	**21.9**
MR2-1	2.39	15.4	**17.8**	**0.55**	1.97	11.1	**13.0**	**0.40**	0.15	**36.3**
MR2-3	8.38	11.7	**20.1**	**0.62**	1.47	7.33	**8.81**	**0.27**	0.35	**129**
MR3-1	10.1	15.6	**25.6**	**0.79**	15.0	11.2	**26.1**	**0.81**	-0.02	**-1.87**
MR3-2	15.6	20.9	**36.5**	**1.13**	16.7	24.3	**41.0**	**1.27**	-0.14	**-11.0**
MR4-1	9.83	16.8	**26.6**	**0.82**	44.8	55.4	**100**	**3.10**	-2.28	**-73.5**

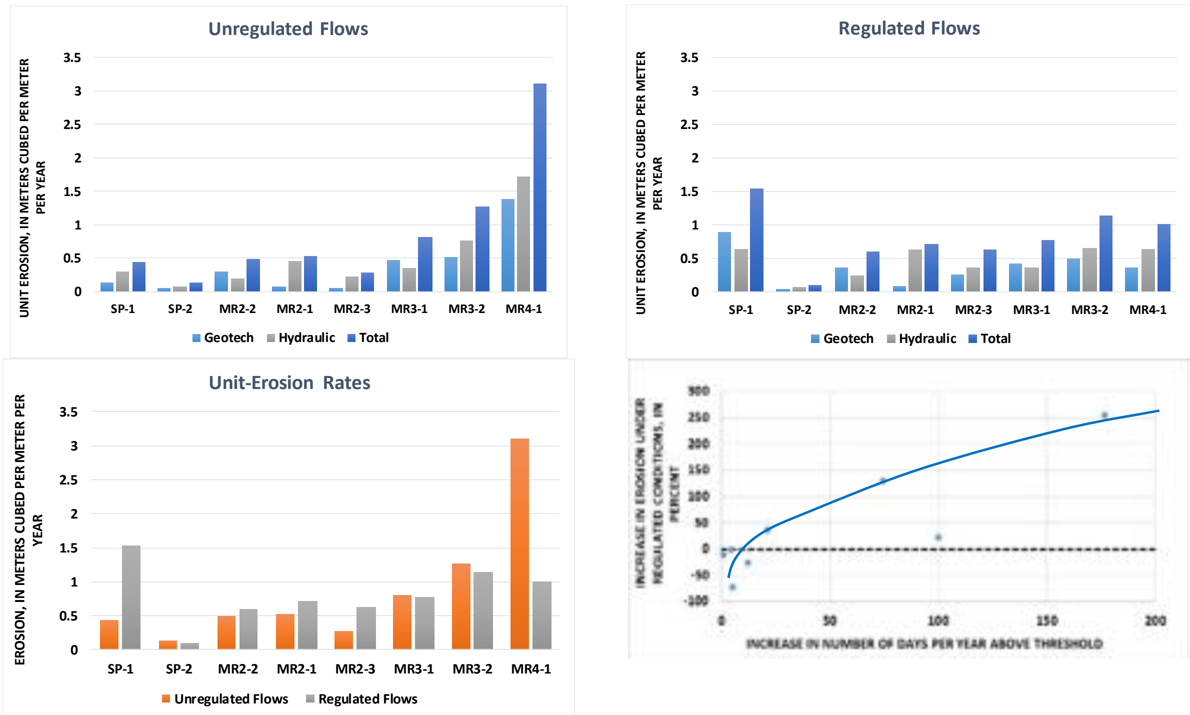


Figure 4. Bank erosion per unit of channel length for unregulated (Top, left) and regulated flows (Top, right), a comparison of the differences (Bottom, left) and the relation with the change in the duration of flows above the erosion thresholds (Bottom, right).

This discussion helps to highlight an important point regarding the change in the flow regime along the study reach. That is, differences in erosion rates are related to the magnitude and the duration of the flows above the erosion thresholds, and not just some overall percentage increase above unregulated conditions. This helps to explain why there may be different responses within a given reach. Table 4 provides a summary of the change in duration of half capacity and capacity discharges (discharges reported by Gippel et al., 2000) for the two flow scenarios. As importantly, it also includes data on the duration of flows at or above the erosion threshold for the 1984-2016 simulation periods. Changes in the duration of half-capacity flows are greater than for capacity flows throughout the study reaches. Channel-capacity flows are less in reach SP1, MR3 and MR4. Only reach MR2 shows an increase in the duration of capacity flows. In contrast, half- capacity flows have greater durations throughout the study area with increases lessening in a downstream direction, from 76 days/y (332-413%) in SP1 to 4 d/y (13%) in MR4 (Table 4). Key are the changes in the duration of flows above the erosion thresholds; 165-202% in SP1, to 109-140% in MR2, to 12% in MR4 (Table 4).

Table 4. Increase in the number of days above half capacity, capacity and the erosion threshold for regulated flows during the 1984-2016 period. Capacity estimates are from Gippel et al. (2000).

Site	Above threshold			Half capacity	Capacity	Half capacity	Capacity
	Increase			Increase		Increase	
	(days)	(days/y)	(%)	(days/y)		(%)	
SP-1	5714	177	202	75.7	-46.4	413	-46.8
SP-2	389	12.0	165	65.6	-44.6	332	-46.8
MR2-2	3234	100	139	20.0	61.2	109	43.9
MR2-1	684	21.2	109	20.1	61.0	109	43.8
MR2-3	2412	74.6	140	20.0	61.1	109	43.8
MR3-1	145	4.5	13	4.2	-21.2	14	-8.4
MR3-2	29	0.9	5	4.2	-21.4	14	-8.4
MR4-1	172	5.3	12	4.2	-20.2	13	-7.2

Further examination of the differences in erosion rates between the unregulated and regulated-flow increasing number of days above the erosion threshold (Figure 4; Bottom, right). The scatter in the relation is in part due to the fact that the magnitude of the increases is not considered here, only the durations.

Summary

Differences between bank-erosion rates under the regulated and unregulated flow scenarios in each reach form an important part of this investigation. Some of the more crucial findings are summarized here:

- Erosion is observed at all study sites under both the regulated and un-regulated flow series
- The most downstream site, MR4-1 has the highest erosion rate under un-regulated flow conditions;
- The most upstream site, SP-1 has the highest erosion rate under regulated flow conditions;
- For un-regulated flow conditions, bank-erosion rates increase with distance downstream from Khancoban Dam.
- For regulated flows, bank-erosion rates are, in general, greater in the reach closest to Khancoban Dam.
- The increase in erosion rates in reaches SP1 and MR2 is at least in part related to the increased frequency and duration of flows that exceed the erosion threshold. A similar relation exists for the increased duration of “half-capacity” flows.
- The increase in bank-erosion rates under regulated flows is generally smaller with distance downstream from Khancoban Dam and downstream in reaches MR3 and MR4, bank-erosion rates are lower under regulated flow conditions compared to un-regulated flow conditions.
- Sites that have decreased rates of bank-erosion rates under regulated conditions, show only limited increases in the duration of flows that exceed the erosion threshold (less than 2 weeks).
- Site SP-2 shows particularly low erosion rates due to the proximity of protective measures and its location on a straight reach.

Thus, the effects of flow regulation on bank-erosion rates are variable, but in a systematic and explicable way. For a given flow scenario, there are differences in erosion rates between individual sites within a specific reach because of differences in the driving and resisting forces that control bank erosion (ie. bank height and angle, bank strength and hydraulic resistance, etc.). The results of the comparison between erosion rates at each site under the regulated and un-regulated flow series, show that erosion is a natural feature of this river in all reaches. Still, there are clear differences in erosion rates between the flow scenarios that are related to the change in hydrologic regime. We see this as being related to the magnitude and duration of flows that exceed erosion thresholds and how the durations of half-capacity and channel-capacity flows have been altered with flow regulation. As expected, in general, the effect of flow regulation on the rates of bank erosion along the Swampy Plain and Upper Murray Rivers decreases as you move downstream, due to the decrease in the magnitude of changes to the flow regime. The outliers such as Site SP-2 hint at the potential effectiveness of mitigation measures to slow rates of erosion. The longitudinal extend of current bank instability is shown in Figure 5 and increases with distance downstream from Khancoban Dam.

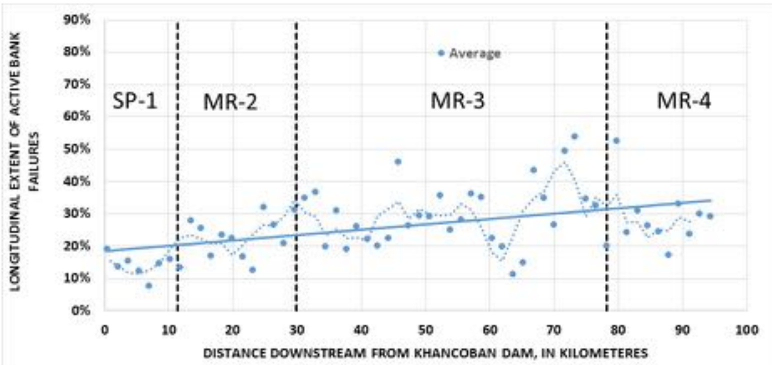


Figure 5. Longitudinal extent of active bank erosion, expressed as *percent reach failing.*

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