

Cost Effectiveness of Bendway Weir Stream Re-Training Techniques in Australia

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Key Points

- Little use of Bendway Weirs in Australia
- Hydraulic modelling study undertaken to determine design and optimise bendway weir configurations at two sites for disaster recovery
- Although effective, bendway weir construction costs exceed those of timber pile fields which provide similar hydraulic benefit
- Negative impacts of bendway weirs are relatively high compared to other comparable techniques
- Other techniques such as pile fields appear to provide the same outcomes but at a far cheaper cost, and which are widely used
- Bendway weirs seem suitable when average annual flows are the main mechanism driving erosion, rather than ephemeral flow regimes

Abstract

Bendway Weirs are a stream-alignment training technique commonly used in the USA since the 1980s and are gaining traction in Australia in recent years. They were the chosen restoration technique at two sites affected by the 2019 Monsoon Trough in Townsville, Queensland. A 2d hydraulic modelling study is undertaken evaluating the hydraulic effectiveness of bendway weirs and the more commonly used technique in Australia, timber pile fields. The hydraulic effectiveness and construction cost estimate of each option at each site is provided. Bendway weirs appears to alleviate adverse bed shear stress conditions against the bank and reduce bed shear stresses for a wider zone than timber pile fields. However timber pile fields reduce shear stress immediately against the bank more effectively than bendway weirs. Comparable timber pile fields can be installed for almost half the price as rock based bendway weirs, and are still cheaper than sand filled geo-bag based bendway weirs. Timber pile fields have less negative impacts than bendway weirs because of their porous nature.

Keywords

Bendway Weir, River Restoration, Erosion, Hydraulic Modelling, North Queensland, Disaster Recovery

Introduction

Bendway weirs were introduced in the 1980s as a means to improve navigation along meander bends of the Mississippi river and to protect the outside bank from erosion (Bigham, 2000). Bendway weirs are low-lying, flat-crested, impermeable g that are often pointed upstream (Figure 1). They are intended to interrupt the complex helicoidal 3d flow patterns that develop around the outside of meander bends (Bigham, 2000). The concept of bendway weirs is to force flow around and over the crest with flows re-directed perpendicular to the crest (Bigham, 2000) (Figure 1). Since the weirs are angled upstream, this will direct flows away from the eroding bank. There are a myriad of design guidelines for bendway weirs. The most recent and comprehensive available are the Bank Stabilisation Design Guidelines (US Department of Interior, 2015).

Bendway weirs were the design element chosen at concept level for recovery of two stream bank erosion sites under Disaster Recovery Funding Arrangements (DRFA) in Townsville, North Queensland. This study evaluates the reductions in hydraulic parameters via 2D modelling resulting from various bendway weir configurations for each site and compares them to more traditional (in Australia) timber pile fields. The cost and hydraulic effectiveness of each option is evaluated for each site.

Background

Many physical modelling studies have evaluated a single bendway weir in a straight flume with a fixed bank (Bigham, 2000). Since 2010 more studies have been undertaken looking at multiple weirs (Bigham, 2000). A recent review of 146 peer-reviewed papers on streambank stabilisation showed that bendway weirs, impermeable spurs and rock vanes are the most commonly evaluated stream bank stabilisation techniques in the USA (Bigham, 2000). Within the review it was found that:

- Angles of bendway weirs pointed upstream from tangent of the bank line ranged from 20 to 135 degrees (Bigham, 2000)
- Heights of bendway weirs never exceeded bankfull width
- Length ranging from 4% to 58% of channel width
- Taller weirs provide the most effectiveness but increase downstream scour near-bank toe likely due to increased wake vortices (Bigham, 2000).

At low flows the bendway weirs produce three zones of flow (Abad, Rhoads, Gunerlap, & Garcia, 2008):

- a region of stagnant or recirculating flow between the weirs along the outer bank;
- a thalweg inward of the weir tips characterised by high velocity core at the surface and decreasing velocities towards the bed and inner bank;
- a shear layer immediately downstream of the weir tips between the recirculating flow and the thalweg.

The weirs interrupt flow around a meander bend and create a sheltered zone of low velocity and bed shear stress behind the weir. Spacing of the weirs ensures that this zone is continued along the bank to be rehabilitated, encouraging sediment deposition and vegetation establishment. However the weirs show localised scour at the river side of each structure

Submergence of the bendway weirs results in an even more complex 3d flow regime around and over the structure. As flow travels over the top of the weir, 3d circulation cell forms on the downstream face of the weir resulting in localised scour (Bigham, 2000). As water level rises over the weirs, flow in the lee of the structures is directed downward towards the bed producing locally high bed shear velocities (Abad, Rhoads, Gunerlap, & Garcia, 2008). The weirs protect the bank toe but may promote retreat induced by enhanced shear forces on the face of the outer bank (Abad, Rhoads, Gunerlap, & Garcia, 2008). This results eventually results in a 'scallop' pattern on the bank.

Critical design parameters of bendway weirs are outlined in Table 1.

Study Sites

Crystal Creek at Mutarnee, Townsville, Queensland

The Crystal Creek Mutarnee site is a 400-500m long river bank that experienced up to 5m of erosion during the 2019 Monsoon Trough flooding event throughout North Queensland. The site is characterised by a near-vertical exposed river bank that is approximately 8m high at the upstream end, with a further 3m deep pool making the exposed bank approximately 11m high. The bank grades to a 5m high bank at the downstream end with a cobble bed at the base. Stratigraphy within the upstream end of the bank consists of indurated clays (silcrete) within the lower bank, overtopped by cobbles and coarse alluvials. At the downstream end of the site the clays are covered by coarse cobbles comprising the bed of the river and the overlying alluvials have partially collapsed, creating a gentler bank slope which has been partially colonized by vegetation.

Crystal Creek in this vicinity is highly active compared to other streams within the area. The downstream end of the reach has migrated over 110m since 1951 while the upstream end has experienced far less bank migration, in the order of 40m since the same date. The exposed indurated clay material in the bottom half of the upstream end of the bank is highly resistant to fluvial scour than the surrounding material. This has ensured that sinuosity cannot be increased and as a result it appears that the stream has incised in the local vicinity, forming the 2-3m deep pool at the base of the escarpment only in recent times as the pool is not evident in aerial photographs from the 1960s.

Stream alignment-training techniques such as bendway weirs comprised of imported angular rock were recommended to be installed at Concept Design phase to re-direct high velocity flows away from the exposed

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bank and pool, encourage sediment deposition and subsequent vegetation colonisation along the eroding river bank.

Black River (White Road to Lores Court), Townsville, Queensland

The site consists of one of the outer bends of Black River, a highly ephemeral system impacted by rural-residential land uses, extensive historical sand extraction operations and extensive groundwater extraction by industrial developments with the catchment. The study site is located between the end of Jensen Road and Lores Court on the eastern side of the bank.

Historical sand extraction operations have affected the overall geomorphology of Black River throughout the majority of the river's length. Over 1,000,000m³ of material has been removed from the river system between 1950 and the early 2000s compared to the average annual recharge estimate of 10,000m³ and 17,000m³ per year (Maunsell Australia Pty Ltd, 2004). Terraces and benches have been lost throughout the river system as a result of the over-extraction of sand resources, resulting in the river system becoming relatively 'flashy' and showing sharp water level rises and decreases in response to rainfall (Maunsell Australia Pty Ltd, 2004).

The river bank of the subject reach has historically been eroding. Topsoils and vegetation have been removed from the river bank since the 1960s, exposing subsoils. The exposed subsoils are magnesian, highly cemented and relatively resistant to erosion. Bendway weirs created from sand filled geobags were recommended at concept design stage to ensure stability of the bank over future flood events, encourage deposition and re-colonisation of vegetation to restore the bank.

Methods

Two-dimensional (2D) hydraulic modelling was undertaken using the TUFLOW engine of both study areas to characterise baseline depths, velocities, stream power and bed shear stresses during various AEPs as well as the 2019 flood event. The 2D modelling was then used to test and optimise various bendway weir scenarios. The net-benefit of the bendway weir designs was evaluated by extraction of a cumulative frequency distribution of maximum bed shear stresses exerted over the near-bank area and comparison with the existing case.

The construction cost of the optimised design was then determined using unit-rates available from local contractors as well as construction costs incurred by Neilly Group Engineering for construction of other river restoration works North and Central Queensland. Where possible, local quotes were acquired from local suppliers such as quarries.

A timber pile field was then proposed for each location and the design iterated through 2d hydraulic modelling (using in-house methods which have been qualitatively verified with field observations) to achieve the optimal design that was within the budgetary constraints. Cost estimates were undertaken for the construction of the timber pile field using in-house rates achieved for construction of other pile fields throughout North and Central Queensland, as well as the equipment and material quotes for each site.

The hydraulic effectiveness of the bendway weir and timber pile field options are compared using cumulative frequency exceedance plots of bed shear stress and direct modelling outputs. Cumulative frequency exceedance plots show the percentage of an area of the model (defined as a polygon by the user) that experiences a maximum BSS at or below a certain value. This allows direct comparison of performance of various designs. Important critical BSS thresholds are included as vertical lines on the cumulative frequency exceedance plots, the values of which have been derived from multiple sources (Fischenich, 2001), (USGS, 2008), (Alluvium, 2014).

The negative impacts of each are evaluated and the construction costs compared.

Optimised Designs

Crystal Creek at Mutarnee, Townsville, Queensland

The bendway weir and pile field options assumed re-grading of the eroding bank from approximately 1V:0.8H to 1V:3H to achieve stability and provide a growth medium for vegetation.

Bendway Weir Solution

Over 26 configurations of rock-based bendway weirs were considered and iterated during the 2d hydraulic modelling phase. However it quickly became evident that the volume of rock required would far exceed the available budget for remediation of the site with the majority of bendway weir options (in excess of 2000m³). This is primarily because of the 2-3m deep pool present at the site where significant rock quantities would be required to raise bendway weir crests to the approximate height of the pool's surface (approximately 3m). The most hydraulically effective bendway weir designs had weir crests 1-2 metres above the water surface elevation of the pool.

The adopted design of bendway weirs included a less than ideal design for full cost estimation to attempt to meet budgetary constraints of the funds available under the DRFA program. The adopted design included:

- 5x bendway weirs installed to 8.2m AHD (pool water level) in the upstream half of the study area within the pool, approximately 15m crest length, and 4m high.
- 4x bendway weirs installed to 9.5m AHD in the downstream half of the study area sitting on the cobble river bed against the bank, approximately 10m crest length, approximately 1.5m high.

All contemporary guidelines recommend bendway weirs to be installed to the same crest elevation along an eroding river bank. There is no guidance on installing weirs to two separate heights, as adopted by the above design, to limit construction cost and adapt to the site characteristics.

The cost estimate to construct the above design was in the order of \$745,000 based on 2,500m³ of rock at a D₅₀ of 450mm required for the bendway weirs.

Timber Piles Solution

A pile field was designed on the same earthworks profile as proposed for bendway weirs, a re-grade of the bank to 1V:3H. 2D hydraulic modelling was used to optimise the pile field in terms of:

- Spacing between individual piles (adopted 300mm)
- Spacing between and total number of pile rows
- Length of pile rows
- Orientation of pile rows

The presence of the pool restricts the ability to install timber piles all the way to the bank toe within the upstream half of the study area, as the re-graded bank toe will be approximately 3m under water. Therefore piles were installed to a location that would be achievable for installation (4m horizontally from the water level) and do not continue all the way to the bank toe.

The comparison between bendway weirs and timber piles at the Crystal Creek site is comparing two designs that are less than ideal and impacted by site constraints. Bendway weirs are not installed to the same crest elevation along the bank, with downstream weirs having a higher crest elevation than upstream weirs, and the timber pile rows are not installed to the bank toe.

During the design process it was revealed that bank battering was not possible at the Crystal Creek site because of landholder constraints. Both options for bendway weirs and timber piles in this paper include bank battering to 1V:3H and therefore do not reflect the final design that will be implemented on the site. The design with bank battering at 1V:3H is included in this paper to ensure that the options are compared on a like-for-like comparison.

Black River (White Road to Lores Court)

Bendway Weir Solution

Three separate designs of bendway weirs were considered at the Black River site. Unlike the Crystal Creek site the bendway weirs at this location were proposed to be created out of sand filled geo-textile bags to lower the construction cost. A cost estimation spreadsheet was obtained from Geofabrics Australia for the ElcoRock series of geobags typically used in coastal engineering.

Three configurations of bendway weirs were considered for the Black River site are included in Table 2. Construction cost estimates for the various options were between **\$430,000 and \$460,000**.

Timber Piles Solution

A timber pile solution was iterated using 2d hydraulic modelling techniques. The resultant design included:

- 19 rows of timber piles installed to protect 550m of the bank, resulting in 550 timber piles
- Rock protection trenches installed around the upper-bank half of each timber pile row, including a key for out-flanking protection. D_{50} of 350mm or 500mm is chosen dependant on pile row
- 300mm spacing between timber piles
- Approximately 25m spacing between timber pile rows

A construction cost estimate of **\$395,000** was calculated for the timber pile field option based on third-party contractor quotes for supply and installation of the timber pile field.

The lower construction cost of the 10m crest length, 3 bag high bendway weir option (CA3) and the lower cost of construction of the pile field allowed a longer length of the bank to be protected while staying under the budget constraints of the project. Therefore the number of pile rows was increased to protect a longer reach of the river bank and the 3 bag high, 10m crest length bendway weir option had two additional weirs added to address the same area. The other bendway weir options were not able to be constructed within the available budget and therefore covered a lower length of the bank. None of the above cost estimates include the revegetation component.

Hydraulic Effectiveness

Crystal Creek at Mutarnee, Townsville, Queensland

Baseline modelling indicates that 35% and 23% of the area near the bank experiences a maximum BSS value at or below the threshold required to erode short native bunch grasses (45N/m^2) during the 50% AEP and 10% AEP respectively (Figure 2). Installation of bendway weirs increases this value to 57% and 48% of the bank which experiences a maximum BSS at or below 45N/m^2 for each event respectively (Figure 2). Comparatively the pile field ensures that the maximum BSS of 45N/m^2 is experienced over 53% and 48% of the area near the bank in the respective events, only a slight improvement compared to the bendway weir option (Figure 2). In this instance the piles and bendway weir options provide a similar performance.

Mapping outputs from the modelling show that the bendway weirs reduce BSS for a wider zone near the bank, particularly in the upstream portion of the site in the 50% AEP (Figure 3). The pile field reduces BSS values more substantially near the bank compared to the bendway weirs (Figure 3) with shear stresses against the bank modelled as $5\text{-}10\text{N/m}^2$.

The comparative performance of the bendway weir and pile field options is shown Table 3. Despite hydraulic performance being comparable, the bendway weirs have a construction cost estimate (\$745,000) considerably higher than the pile field option (\$465,000).

Black River (White Road to Lores Court)

Unlike the Crystal Creek site the construction cost estimate for various bendway weir configurations is similar at the Black River site. Comparison is made between each bendway weir option and the optimised pile field as cumulative frequency exceedance plots in Figure 4.

The longer bendway weir option (Option 3), with 20m long weirs, reduces bed shear stress across the most area of the bank as outlined by the cumulative frequency exceedance plots (Figure 4, Figure 5). Approximately 60% of the area near the bank experiences shear stresses in the order of 23N/m^2 under this option, compared to 50% of the bank under the 4 bag high bendway weir (Option 2) or pile field options for the 50% AEP (Figure 4).

The pile field option has increased performance over all remaining bendway weir configurations. At higher shear stresses above 38N/m^2 the pile field has better performance even compared to the option with longer (20m) bendway weirs (Option 3) as outlined in Figure 4.

For the 10% AEP the 4 bag high bendway weir option (Option 2) provides better shear stress reductions than all other options considered (Figure 4). Approximately 70% of the area near the bank has a modelled shear stress of the following value or lower:

- 35N/m^2 for the 4 bag high, 10m long bendway weir option,

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- 58N/m² for the pile option,
- 60N/m² for the 12x weir, 10m long and 3 bag high option (Option 1),
- 65N/m² for the 10x weir, 20m long, 3 bag high option (Option 3), and
- 72N/m² for the existing case

Overall the pile field option performs slightly better than the 3 bag high (Option 1) bendway weir and longer bendway weir (Option 3) option in the 10% AEP but is outperformed by the 4 bag (Option 2) option in the higher event.

Performance of each option with construction cost estimate is provided in Table 4. The pile field option is the second-most hydraulically effective option for the cheapest construction cost.

Impacts

Bendway Weir Localised Impacts

A commonly known impact of bendway weirs is the scalloping of the bank between each weir. This is caused by circulation cells forming behind each weir which impact the bank. This will have a particularly large impact at the Black River (White to Lores) site as the loss of topsoils overlying the exposed subsoils is the primary mechanism of erosion. Scalloping of the bank between bendway weirs will work against the primary objective of the river restoration measures.

Modelling undertaken for this study identified that flow patterns will occur that will lead to scalloping of the bank behind each bendway weir (Figure 6). These flow patterns occur in the modelling until water exceeds the crest of the weir by more than 0.5m, meaning that circulation cells will form during low flows below the 50% AEP which are more frequent.

The weir crest also causes increased bed shear stresses to be exerted on the bank, on the bank side where the crest of the geobag wall intercepts the bank material (Figure 7). This highlights the requirement to key in the bendway weirs horizontally into the bank to minimise this occurrence. This increases the cost estimate for construction as either more bags are required to address this scour or rock protection is required. Scour also occurs on the downstream side of each bendway weir during flows reaching the crest level as waters spill over the crest as well as off the river-side end of the bendway weir (Figure 7).

Pile Field Localised Impacts

Comparatively, small amounts of localised scour occurs in pile fields. Scour is immediately noticeable between each pile as localised flows rush to travel through the gap between the piles. However, the overall effect of the pile field is to reduce the general velocity near the bank. Like bendway weirs localised scour can occur at the river-end of each pile row.

Installation of piles with no bank battering or with considerable stickup between the bank-side pile and the river bank can increase the risk of out-flanking and erosion on the bank side of the pile field. This occurs as waters rush between the first piles and the exposed, near-vertical, sections of the bank that the piles are installed against. This process is evident in modelling results shown in Figure 8. Rock armouring is typically installed in this area to mitigate this effect. This has been incorporated into the design and cost estimation.

Assumptions and Limitations

- Modelling undertaken for this study is 2d hydraulic modelling using TUFLOW. 2d hydraulic modelling will not capture all energy losses associated with timber pile fields. The modelling does not account for sub-grid scale energy losses and scour through the piles. Therefore the hydraulic performance of the timber pile fields in reducing bed shear stress is likely to be under-stated in 2d modelling results. Localised impacts such as scour between individual piles, is not evident in the modelling results.
- Many of the comparisons in this paper are not a direct like-for-like comparison. Rather the comparison is between what options (bendway weir or pile field) would be installed at a particular site for a fixed budget. This then highlights the cost effectiveness of the bendway weir or pile field for implementation at a site.

Conclusions

Bendway weirs are an alignment re-training technique commonly used throughout the USA and there is increased curiosity about implementation of the method in Australia. A comprehensive evaluation was undertaken via detailed modelling and cost estimation between the effects and hydraulic impacts of bendway weirs and pile fields, which are commonly used throughout Australia.

The evaluation found that the hydraulic benefits of bendway weirs are similar to timber pile fields, and can exceed pile fields in higher AEP events if higher bendway weirs are installed. However but timber pile fields can be installed for much lower cost while achieving similar hydraulic effects as standardized bendway weir designs, therefore making them more effective. There are less negative impacts associated with timber pile fields than bendway weirs, primarily because the timber pile rows are porous compared to the impermeable bendway weirs.

Installation of rock keys is critical for the success of either option to minimise the risk of out-flanking. Bendway weirs appear, from the modelling, to have increased risk of erosion bank side of where the crest is exposed than timber piles, therefore increasing the out-flanking risk and highlighting the requirement for keys to be installed within the bank.

Acknowledgments

Townsville City Council Sustainability Services

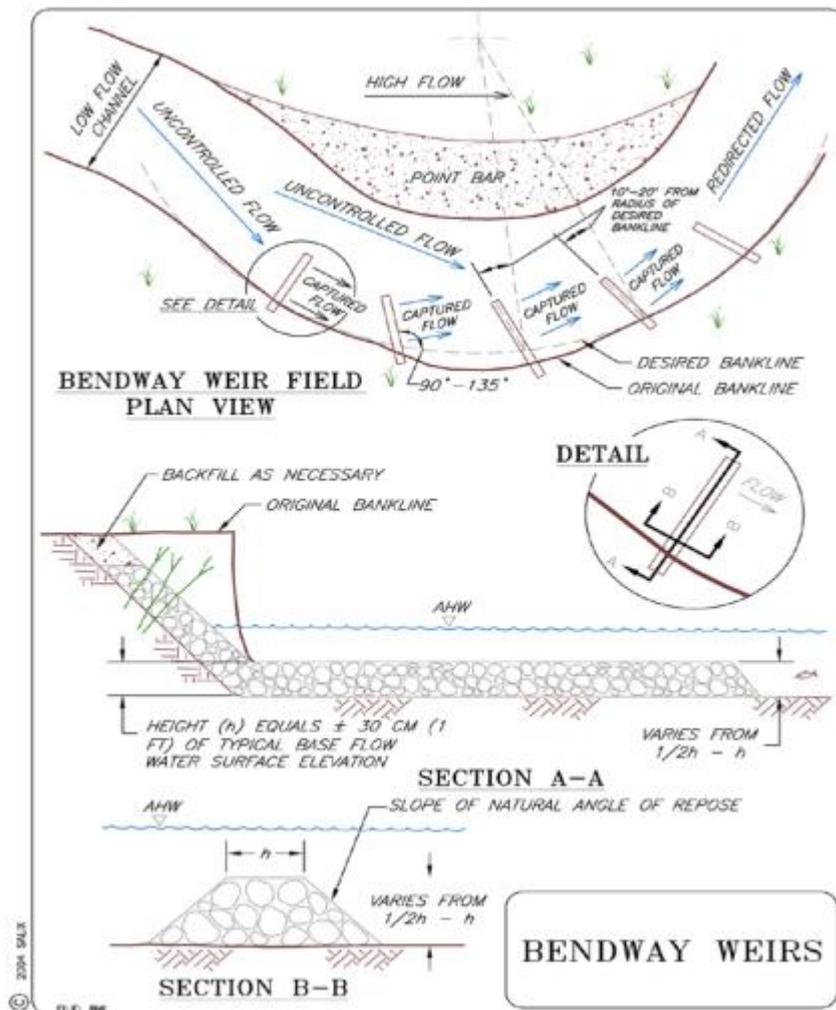


Figure 1. Typical details of a bendway weir (US Department of Interior, 2015)

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Table 1. Adopted Bendway Weir Design Parameters for Crystal Creek

Bendway Weir Design Parameter	Guidance (US Department of Interior, 2015)	Adopted
Crest Width	2-3x D ₁₀₀	1.8m
Orientation	10-30 degrees upstream from perpendicular to flow	20 degrees from perpendicular to flow (110 degrees from the toe of bank line)
Length	1/3 to 1/2 active channel width	Determined by height for site 1
Height	Mean Annual Flow + 300mm; OR "Lowest point of vegetation along the river bank"	Iterated via hydraulic modelling including: <ul style="list-style-type: none"> Crest at pool elevation (8.5m AHD) Crest at 9.5m AHD (63% AEP) Crest at 10m AHD (50% AEP)
Weir Spacing	Various equations dependant on channel top width, weir length and channel radius	Iterated via 2d hydraulic modelling. Spacings between 20-50m tested.
Rock Size	Determined by standard rock sizing equations	D ₅₀ = 450mm

Table 2. Three Bendway Weir options evaluated for Black River (White to Lores Road)

Parameter	Option 1	Option 2	Option 3
Length of Bank Protected (m)	550m	465m	465m
Number of weirs	12	10	10
Weir Crest Length	10m	10m	20m
Weir Height (number of bags)	3 bags	4 bags	3 bags
Weir Height (metres above bed level)	1.95m	2.6m	1.95m
Weir orientation	20 degrees back into the flow direction from perpendicular		
Weir spacing	Approximately 50m		
Bank Key Depth	2 bags	2 bags	2 bags
Total number of bags	864	840	900
Cost Estimate	\$440,000	\$430,000	\$460,000

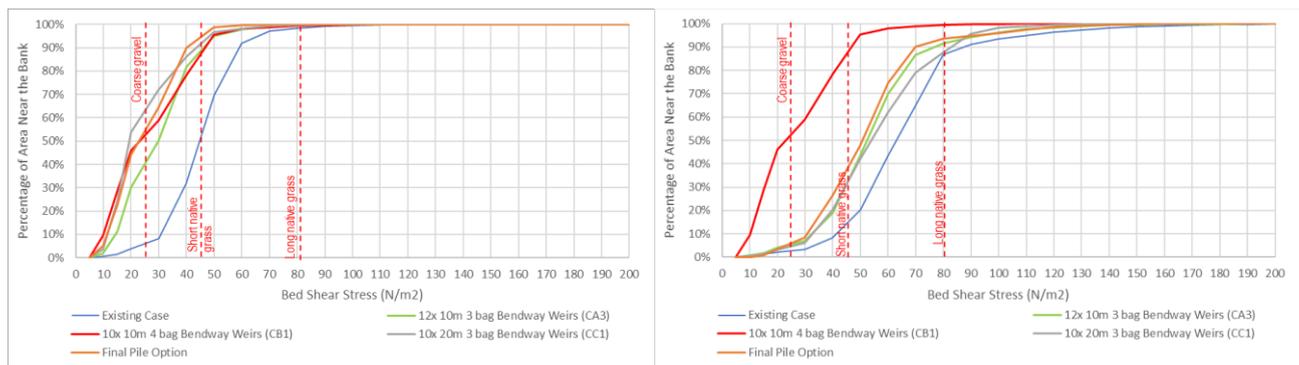


Figure 2. Cumulative exceedance frequency graph for BSS at the Crystal Creek site for the 50% AEP (left) and 10% AEP (right)

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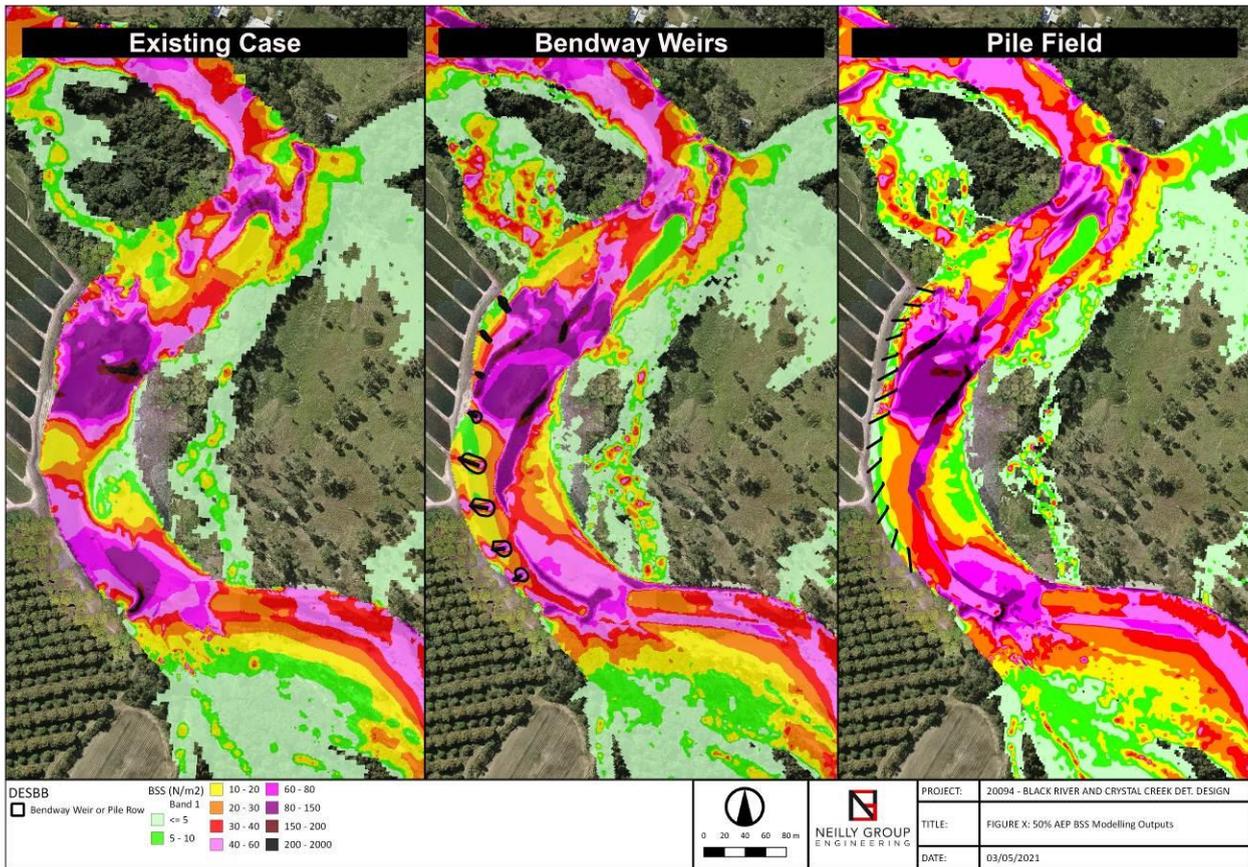


Figure 3. Model outputs of BSS for the existing case, bendway weir and pile field options for Crystal Creek for the 50% AEP event

Table 3. Bed shear stress performance of Bendway Weirs vs Pile Field for Crystal Creek.

Option	Existing Case	Bendway Weirs	Piles
50% AEP Cumulative Frequency	20% area near-bank below	30N/m ²	20 N/m ²
	50% area near-bank below	55 N/m ²	41 N/m ²
	70% area near-bank below	69 N/m ²	58 N/m ²
	90% area near-bank below	110 N/m ²	100 N/m ²
10% AEP Cumulative Frequency	20% area near-bank below	42 N/m ²	26 N/m ²
	50% area near-bank below	63 N/m ²	47 N/m ²
	70% area near-bank below	85 N/m ²	66 N/m ²
	90% area near-bank below	122 N/m ²	110 N/m ²
Construction Cost Estimate (excluding revegetation)		\$745,000	\$465,000
Cost Estimate Reliability		Moderate (±30%)	High (±10%)

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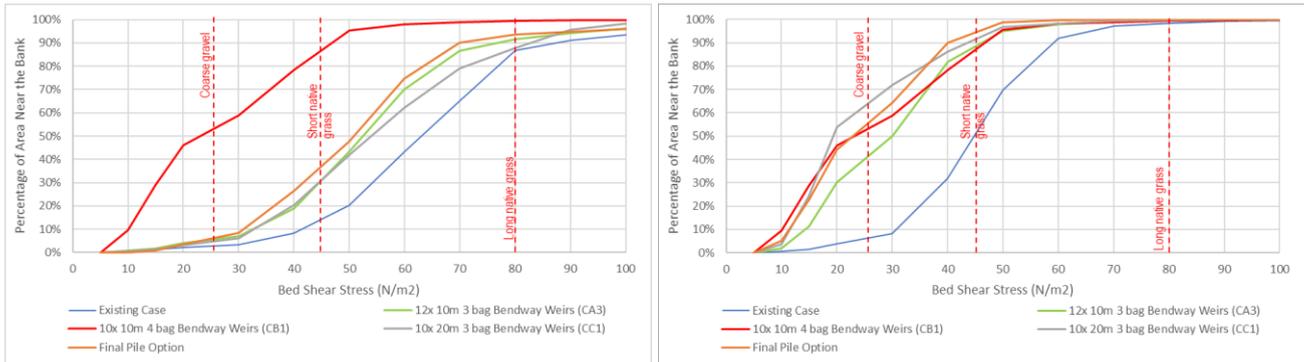


Figure 4. Cumulative frequency exceedance curve for BSS in the 50% AEP for all options modelled for the Black River (White to Lores Road) site

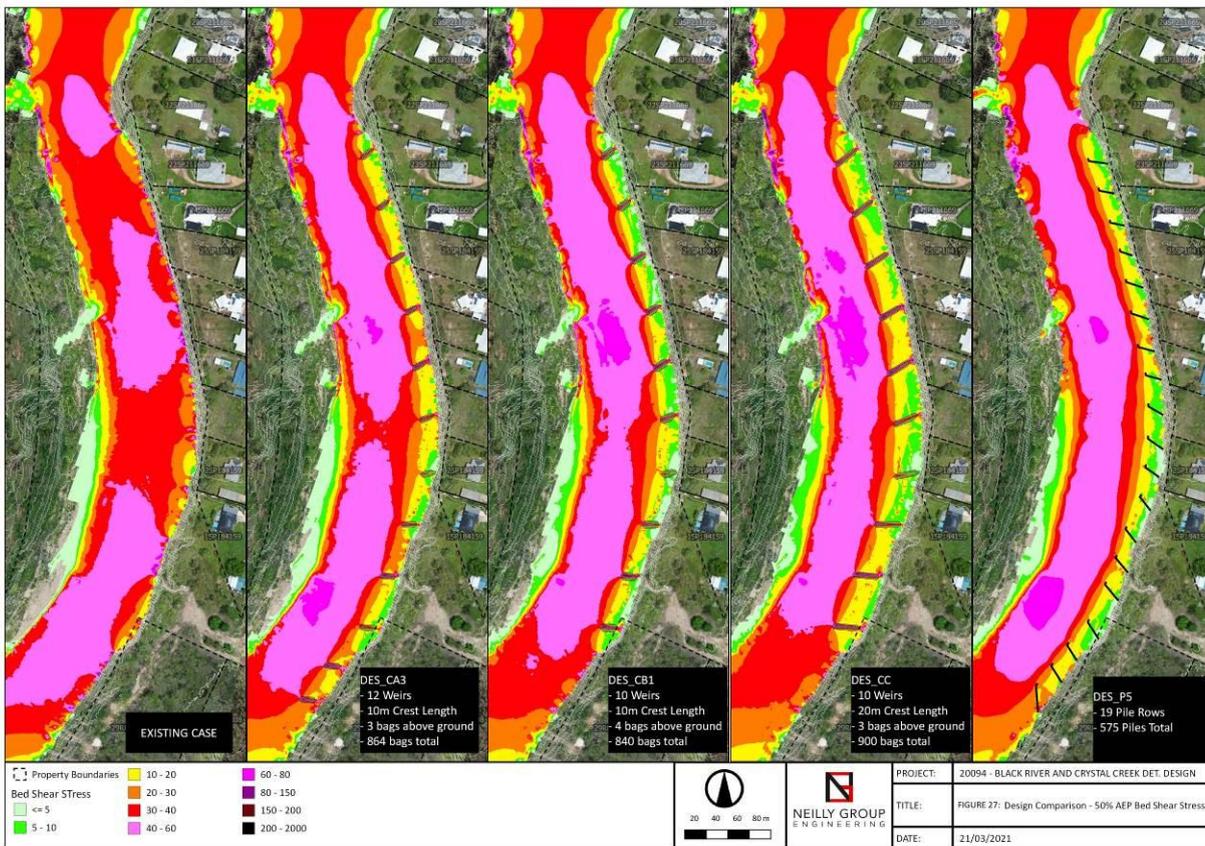


Figure 5. Model outputs of BSS for the existing case, bendway weir and pile field options for the Black River (White to Lores) site

Table 4. Bed shear stress performance of each design option for Black River (White to Lores Court). Values are in N/m^2 unless otherwise stated.

		Bendway Weirs			Pile Field Final Pile Field Design
Code		Option 1	Option 2	Option 3	
Configuration		12x 10m weirs 3 bag high	10x 10m weirs 4 bag high	10x 20m weirs 3 bag high	
50% AEP Cumulative Frequency	20% area near-bank below	16 N/m^2	12 N/m^2	14 N/m^2	14 N/m^2
	50% area near-bank below	30 N/m^2	23 N/m^2	20 N/m^2	23 N/m^2
	70% area near-bank below	37 N/m^2	37 N/m^2	29 N/m^2	32 N/m^2

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	90% area near-bank below	47 N/m ²	47 N/m ²	45 N/m ²	40 N/m ²
10% AEP Cumulative Frequency	20% area near-bank below	40 N/m ²	13 N/m ²	40 N/m ²	37 N/m ²
	50% area near-bank below	52 N/m ²	24 N/m ²	53 N/m ²	51 N/m ²
	70% area near-bank below	60 N/m ²	35 N/m ²	64 N/m ²	58 N/m ²
	90% area near-bank below	75 N/m ²	47 N/m ²	84 N/m ²	70 N/m ²
Length of Bank Protected		550m	465m	465m	550m
Construction Cost Estimate (excluding revegetation)		\$440,000	\$430,000	\$460,000	\$395,000
Cost Estimate Reliability		Moderate (±30%)	Moderate (±30%)	Moderate (±30%)	High (±10%)

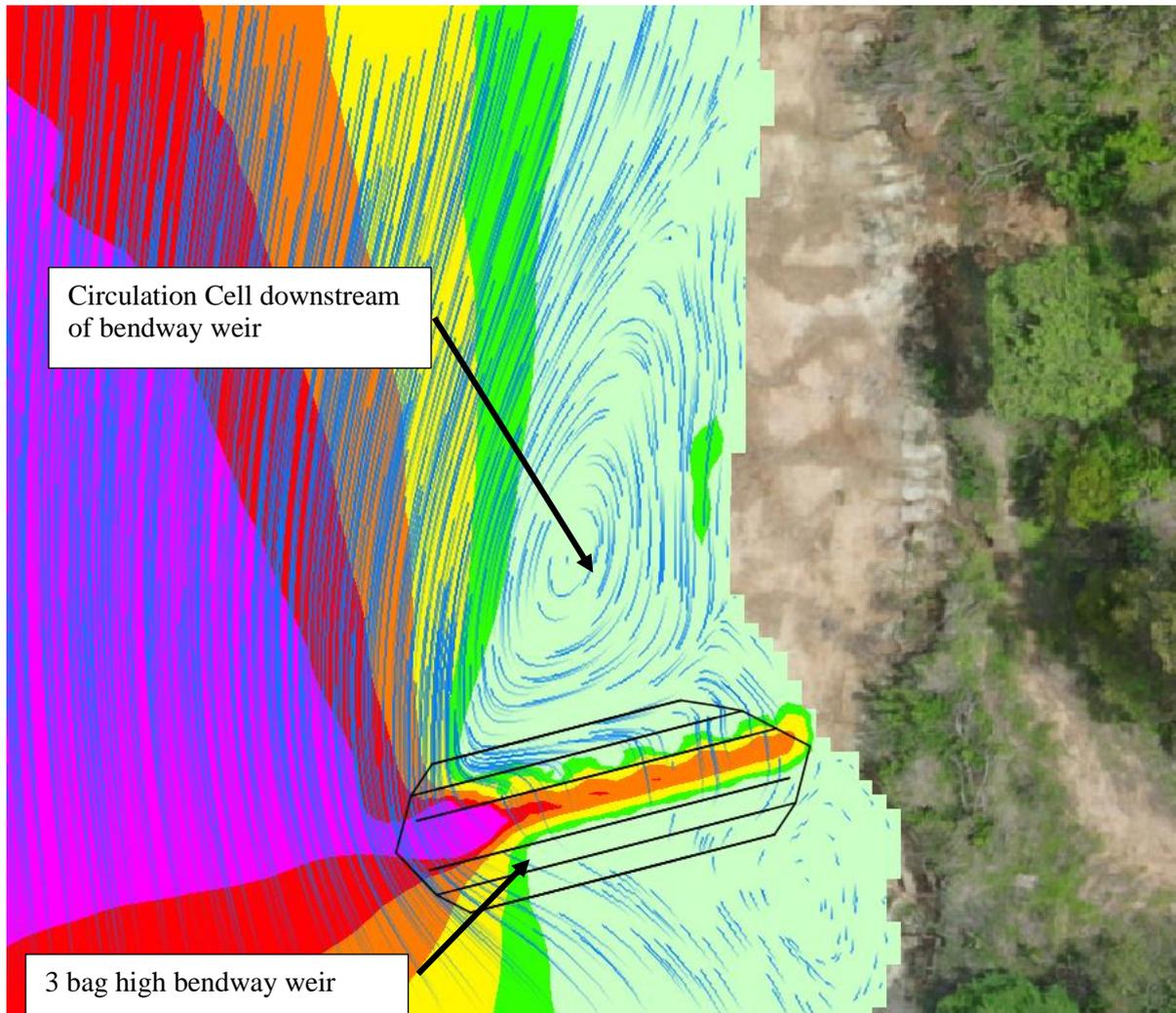


Figure 6. Circulation cells forming upstream and downstream of bendway weirs installed against the bank during a low flow event (water elevation approx. 0.4m above bendway weir crest)

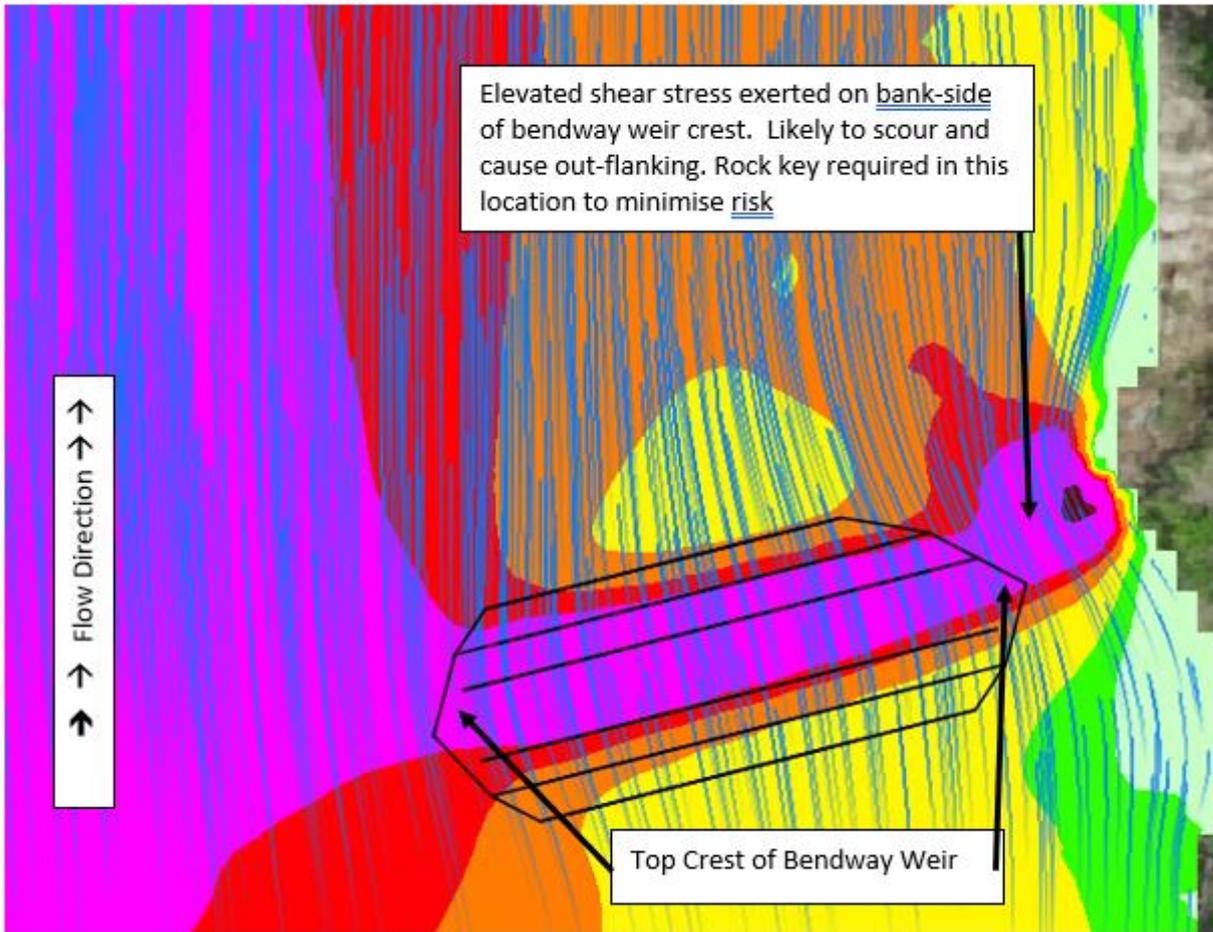


Figure 7. Localised impacts of bendway weirs shows high shear stress exerted on the bank adjacent to bendway weir, highlighting risk of out-flanking and the requirement for a key



Figure 8. Flow field through a pile row in the northern half of the study area

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