

# Pile style – how advanced modelling can inform design of pile field stream bank stabilisation

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## Key Points

- Pile field groynes are extensively used for stream bank stabilisation works across Great Barrier Reef (GBR) catchments, however current design approaches rely on empirical approaches resulting in potential inefficiencies.
- Contemporary three-dimensional (3D) hydrodynamic modelling approaches present an opportunity to improve user-friendly, widely adopted two-dimensional (2D) models to recapitulate the 3D results more closely.
- We have selected a site with unique hydro-geomorphic characteristics intended to exemplify the hydraulic effectiveness of pile field groynes.
- We present the methodology and preliminary results of a work-in-progress, where the hydrodynamic impact of pile fields at a site on the Mary River are simulated using a 3D model, with a view to correlate these with 2D model results in the future.

## Abstract

Pile field groynes have been extensively used for stream bank stabilisation across the Great Barrier Reef (GBR) catchments, accounting for over \$10 million estimated expenditure in the past five years. To enable more efficient allocation of funding to sediment reduction programs resulting from cost-effective design, improved understanding of the hydraulic effectiveness of pile fields is required. This study explores improvements to pile field design using three-dimensional (3D) hydrodynamic modelling approaches. A study site on the Mary River, Queensland, was selected to assess the impact of key parameters (e.g. channel width, radius of curvature) on the hydraulic effectiveness of pile fields. A 3D hydrodynamic model was used to investigate the effects on the flow field (e.g. shear stress, velocity) arising from various flow states through a pile field. Results from the 3D model were correlated to results from a two-dimensional (2D) hydraulic model (the typical tool used by river engineers). We discuss an ongoing investigation, where we aim to develop more accurate approaches for modelling pile fields in more accessible 2D models. These assessments will inform the development of guidelines assisting designers to understand the potential impacts of pile fields on river hydraulics and sediment transport processes.

## Keywords

Pile fields, groynes, stream bank stabilisation, river restoration, hydraulic modelling

## Introduction

Groynes (also known as lateral dikes or spur dikes) are placed in sequence along streambanks to disrupt near bank flow lines and mitigate bank erosion. Pile fields, constructed from timber piles, are one example of permeable groyne structures which have been used extensively in stream bank stabilisation projects in Australia (Figure 1). However, hydraulic impacts of pile fields have not been well characterised to date using contemporary 3D modelling.

A primary function of pile fields is to mitigate bank erosion by reducing near bank flow velocity and shear stress, increasing fine and coarse sediment deposition, and promoting vegetation establishment (Alauddin, et. al, 2011, and Carling, et. al, 1996). Timber piles have a finite design life (10-15 years). The establishment of vegetation along the lower bank can help provide long term stability to the system beyond the design life of the works.

Current pile field design approaches are outlined in the Technical Guidelines for Waterway Management (DES, 2007). Two design approaches are presented in the guidelines. The first is the notional line of attack approach which is neither precise nor determinate and has no basis in stream hydraulics or geomorphic processes. The second is the sheer stress reduction approach which is based on both research undertaken by Dyer (1995) using a straight flume with alternative pile field configurations, and research into the effective energy gradient on stream meander bends of varying radius of curvature. Both of these approaches have strong anecdotal evidence of success, however this may be due to the design approaches being overly conservative (i.e. more piles are used than are required). Advancements in 3D hydrodynamic modelling in recent years provides the opportunity to improve our understanding of the complex flow responses surrounding these permeable groyne structures.

This study uses 3D hydrodynamic modelling to assess the hydraulic effectiveness of pile fields. A better understanding of the hydraulic impacts of these structures may inform more cost-effective pile field design, resulting in more efficient allocation of funding to sediment reduction programs within GBR catchments.



**Figure 1. Recently constructed pile field groynes on the Mary River (left), the largest river bank stabilisation project in Australia utilised pile field groynes on the Fitzroy River (right).**

## **Background**

A pile field comprises individual timber piles which are embed into the riverbank. The primary function of pile fields is to reduce near bank flow velocity and shear stress, converting sites of scour to depositional environments (DSE, 2007). Groynes increase flow resistance, decelerated flow, and promote deposition of fine and coarse sediment within embayments (the area between two groynes) (Rutherford et. al., 2007). Reduction of near bank velocity results in a reduction in shear stress (i.e. hydraulic force) acting on a streambank, and therefore a reduction in fluvial scour (Blackham, 2006).

### *Impacts of groynes on river processes*

Permeable groynes impact the morphodynamics and hydrodynamics of rivers through three key processes; scour near groynes, modification of velocity distribution across the river channel, and deposition within embayments. Pile field structures, despite their use in reducing fluvial scour in the near bank zone, themselves are subject to scour. Pile fields restrict flow, influencing the pressure distribution around the structure and resulting in local scour. Flume studies and field observations suggest that scour occurs uniformly around permeable piles, and initiates at the riverward end of permeable groynes, due to flow separation and the formation of eddies (Teraguchi, et. al., 2011; SCRC, 1991; Zhang et. al., 2009; and Dyer, 1995).

Permeable pile fields additionally impact velocity distribution across the river channel. In a flume study Zhang (2009) found that longitudinal flow velocities are reduced when flow approaches and passes through permeable groynes. Conversely, flow velocities in the main channel are significantly increased. Groynes also disrupt the erosive helical flow pattern characteristic of meander bends (Abad et al., 2008; and Jia et al., 2009). Reduction of flow velocity within pile field embayments results in deposition and accumulation of sediments and seeds, creating favourable conditions for riparian vegetation establishment (Carling, et. al, 1996). The establishment of vegetation also influences river hydrodynamics; increasing hydraulic roughness, assisting in the reduction of near bank flow velocity, and stabilising deposited sediments (Rutherford et. al., 2007).

### **Key factors which impact on pile field performance**

Several key factors impact the performance of pile field groynes, including groyne spacing, porosity, length, angle, and groyne and pile height:

- Groyne spacing impacts shear stress reduction and is related to overall bed shear stress between groynes (Peng et. al., 1997). Optimisation of pile field spacing would ideally result in a target cumulative shear stress reduction in a downstream direction while maximising cost-effectiveness.
- Groyne porosity (based on pile cross-sectional area and spacing between individual piles) affects both near bank velocity and scour. Porosity influences velocity profiles in embayments (Dyer, 1995), and is inversely related to scour depth (Nasrollahi et. al., 2008).
- Groyne length is dependent on the desired degree of alignment training and is correlated to construction cost. A long pile field which extends past the existing toe of bank significantly alters cross-sectionally hydraulics, pushing the thalweg away from the toe of bank and realigning the river (Rutherford et. al., 2007).
- Groyne angle, relative to flow, does not have significant impact on the hydrodynamic performance of pile fields (Dyer, 1995; and SCRC, 1991). However, a slight downstream orientation allows for debris shedding.
- The pile height above the riverbed impacts the downstream distance influenced by the pile field (i.e. shear stress reduction) (DSE, 2007, and Dyer, 1995). Pile field elevation up the bank is also a critical design factor, as insufficient elevation can lead to scour of the upper bank, potentially outflanking the works.

### **Challenges associated with modelling pile fields in one-dimensional and two-dimensional models**

One-dimensional (1D) models can simulate the magnitude of hydraulic parameters, such as velocity and shear stress, at delineated channel cross-sections. However, 1D models are unable to model complex flow patterns associated with pile fields due to inability to capture variations in hydraulic parameters across a section (and in the areas between cross-sections), and the hydraulic effect of changes in cross-sectional geometry and meander bends.

2D models can simulate both the flow direction and velocity at hydraulics structures. Therefore, 2D models can more accurately simulate hydraulic behaviour of flows around pile fields. However, like 1D models, 2D models are unable to simulate complex three-dimensional flow (depth) patterns associated with pile fields. These include flow separation and associated scour around pile fields, and the erosive helical flow pattern characteristic of meander bends. These three-dimensional flow characteristics are key drivers of scour and riverbank erosion and have considerable impact on pile field performance.

Advancements in 3D hydrodynamic modelling in recent years provide the opportunity to improve our understanding of the complex flow and turbulence responses around permeable groyne structures. This study utilises high resolution 3D hydrodynamic modelling to assess the hydraulic effectiveness of pile field groynes.

## **Methods**

### **Study site**

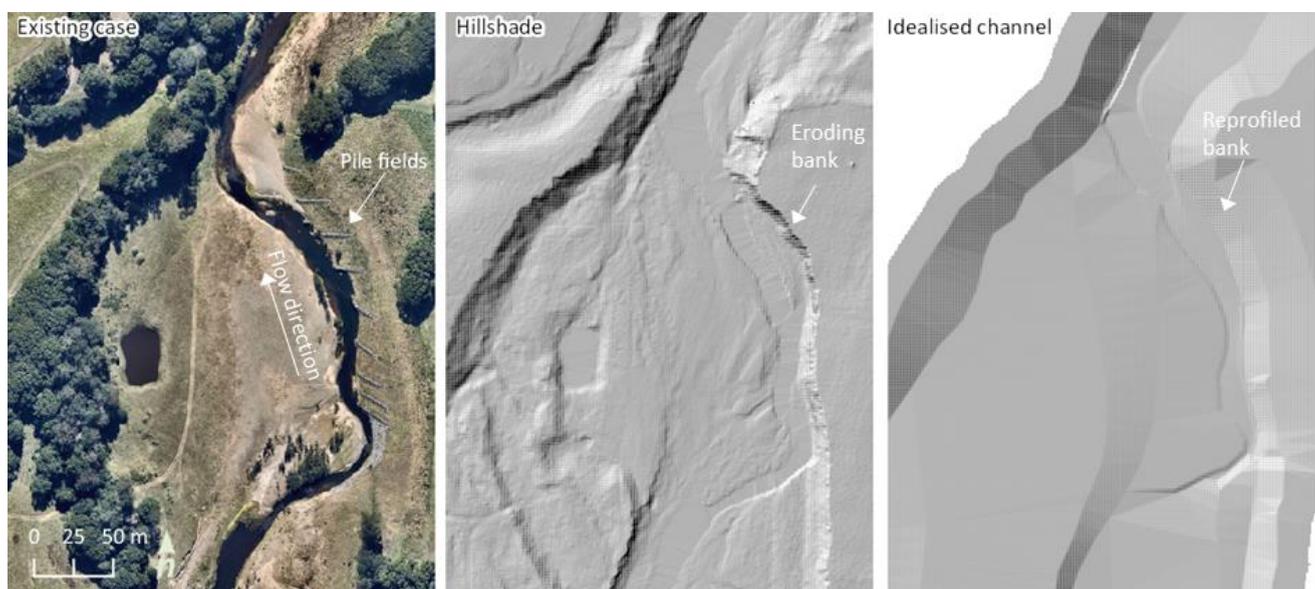
The Mary River is located in South East Queensland, Australia. The river system rises in the Conondale Range and flows in a north easterly direction, through Kenilworth and Gympie, discharging into the Great Sandy Strait. The Mary River Carters pile field site is located approximately 1.7 km upstream from the Eumundi-Kenilworth Road crossing. Prior to stabilisation works, the site consisted of a steep to near-vertical bank, approximately 8 to 9 m in height, and 240 m in length.

The channel adjacent to the study site has been highly modified through sand and gravel extraction. Historical channel deepening processes have been identified in the reach, with the channel undergoing approximately 1 -2 m of deepening since 1958 (Alluvium, 2014). The deepening occurred in response to the sand and gravel

extraction, and subsequent loss of the riverbed armor layer. Excess stream power arising in response to the deepening has been dissipated through channel widening and meander migration. Erosion at the site, prior to works, resulted over 130 m of bank retreat since 1968.

Bank stabilisation specifications for the Mary River Carters site were collated based on available data which included design reports, design drawings, spatial data, and 12d designs. The bank stabilisation works at the site include bank reprofiling (to a gradient of 1V:3H), installation of pile fields along the toe of bank, establishment of riparian vegetation along the reprofiled bank and overbank, and installation of rock revetment at the upstream end of the works (Figure 2).

Alternative pile field design configurations were developed for the site. These configurations were informed by the existing pile field design at a site, and consisted of variation in key design elements, including the number of groynes and spacing between groynes (i.e. distance to downstream pile field), spacing of individual piles (i.e. groyne porosity), and the exposed height of piles (above the riverbed). These pile field configurations are intended to exemplify the impact of key design elements on the hydraulic effectiveness of pile field groynes (Table 1).



**Figure 2. The Mary River Carters study site showing the existing pile field design (left), hillshade of the pre-works terrain (middle), and the idealised terrain model.**

**Table 1. Pile field configurations – Mary River Carters (green indicates variation).**

Pile field design elements	Base case	Existing case	Design 1	Design 2	Design 3	Design 4	Design 5	Design 6
Pile field spacing (m)	-	9, 11, 20, 24, 27, 24, 25, 24.	7.5, 7.5, 7.5, 20, 20, 20, 20, 20, 20.	10, 10, 30, 30, 30, 30.	as per existing	as per existing	as per existing	as per existing
Number of pile fields	-	9	11	8	9	9	9	9
Porosity (% open)	-	50%	50%	50%	33%	70%	50%	50%
Pile height above riverbed (m)	-	1.5	1.5	1.5	1.5	1.5	1	2
Pile diameter (mm)	-	300	300	300	300	300	300	300

### Three-dimensional hydrodynamic modelling

3D hydrodynamic simulations for this study were performed using the hydrodynamic component of Aquatic Ecosystem Model (AEM3D). AEM3D is an environmental fluid dynamics model which solves the unsteady, viscous Navier–Stokes equations for incompressible flow using the hydrostatic assumption for pressure (Hodges, et. al. 2021).

An idealised terrain model (1 m resolution) for the site was developed from LiDAR datasets for input into the 3D model (Figure 2). These terrain models were developed with the aim to reduce “noise” in model outputs

(i.e. bed shear stress) caused by artifacts in the raw terrain models. The idealised channel captures key geomorphic features of the site, including bank height, channel width and sinuosity, geomorphic units (i.e. benches), and reach slope. The terrain model incorporated a reprofiled bank (to a gradient of 1V:3H); to ensure the impact of pile fields design elements, rather than the bank morphology, was being assessed. A shapefile of the existing pile field configuration was then developed for input into the AEM3D model, with the elevation (m AHD) of the top of each individual pile assigned to each pile polygon. For the existing pile field scenario, pile fields were built into the model terrain files.

The model domain was represented with a variable horizontal grid of 0.1 m by 0.1 m in the pile field region, expanding out to a 5 m by 5 m grid in the channel, and a vertical resolution of 0.5 m. Three design flows were identified to test the hydraulic effectiveness of pile fields under various flow elevations relative to pile and bank height. Flow height at the top of the riverward piles (i.e. flow height 1.5 m above the bed), flow at the top of the landward piles, and an approximately 0.5 EY flow (all piles submerged). For each design flow the no pile field case was run for 6 hours to identify a “steady-state” surface height for model initialisation. This initial height was then used for the 2 grids at the site (no pile field, and existing pile field configuration). Each grid was run for 30 minutes, which took up to 20 hours to simulate for the higher flow rates. The model used a 1 second time step.

### *Two-dimensional hydrodynamic modelling*

2D hydrodynamic simulation for this study were performed using HEC-RAS (version 6.0); using the Shallow Water Equations (SWE). HEC-RAS terrain modification tools enabled the modification of the idealised terrain to incorporate the pile field structures.

As far as possible, the 3D modelling procedures were replicated for the 2D model setup; to enable comparison of 3D and 2D model results. RASmapper was used for the HEC-RAS 2D model set up. The idealised terrain model, developed for AEM3D, was input into the 2D model. Terrain modification tools were then used to build the pile fields into the terrain by overriding terrain elevation values.

A 2D computational mesh was used to delineate the model domain, with a base resolution of 5 m by 5 m, and a higher resolution adjacent to the piles fields (0.2 m by 0.2 m). A spatially varying land cover layer was then created; Manning’s n regions were delineated based on analysis on high resolution aerial imagery. For each design flow an unsteady flow simulation was performed, however, the peak flow was run for an extended period (3 hours) to simulate a “steady-state”. The model used a variable time step, with an initial computational interval of 0.2 seconds.

The 3D and 2D models use different bed shear stress calculations, therefore the percentage change in bed shear stress was considered of most useful comparator between the two.

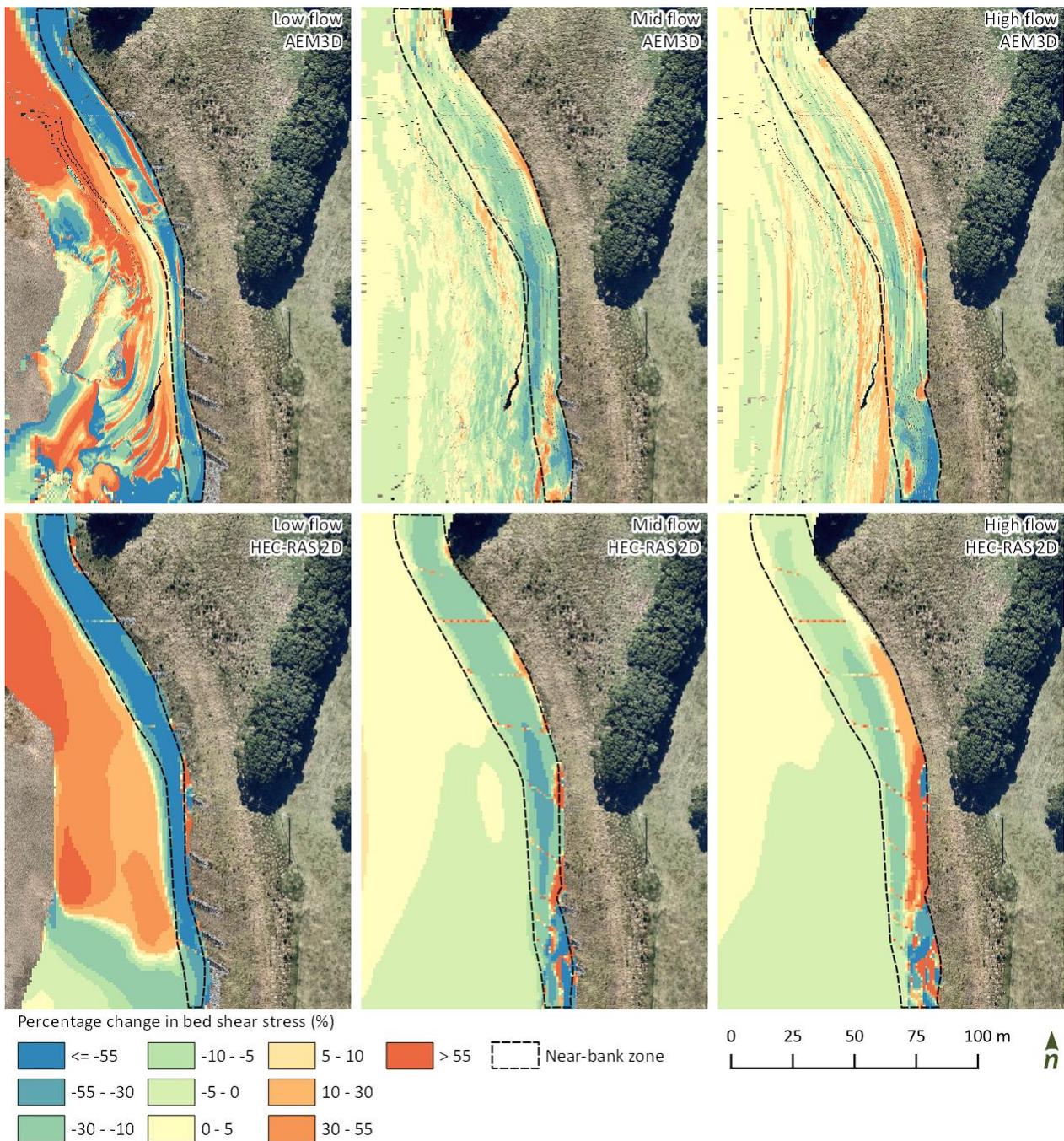
## **Results**

The 3D shear stress results were averaged over a 10-minute period at peak flow to eliminate discrepancies in flow oscillations between the pile field and no piles field scenarios. Where the bed shear stress for the no pile field scenario was very small compared to the existing pile field scenario the percentage change was very high in isolated cells. To eliminate extreme outliers, cells with percentage change >5000% were nulled (this accounted for < 0.2% cells in each of the 2D and 3D data sets).

Spatial variation in near-bank percentage change in bed shear stress for the three flows modelled in AEM3D and HEC-RAS 2D are shown in Figure 3. In the 3D simulations longitudinal bands of shear stress reduction are evident stream-wise through the pile fields. In comparison, the 2D simulations shown discrete zones of shear stress reduction within the embayments. In both the 3D and 2D simulation the shear stress reduction is most notable within the most upstream embayments.

A box plot of the variation in percentage change in bed shear stress is shown in Figure 4. As seen in this figure, the 3D and 2D results show a similar tendency with the pile fields resulting a greater reduction in percentage change in bed shear as flow height decreases. For the 2D low flow simulation the median change in bed shear stress was -66%, compared with -46% in the 3D simulation (i.e. the 3D model indicated that 50% of the near-bank zone had a bed shear stress reduction of at least 46%). While displaying lower median reduction in bed shear stress, the 3D model had higher interquartile range compared with the 2D model, suggesting higher

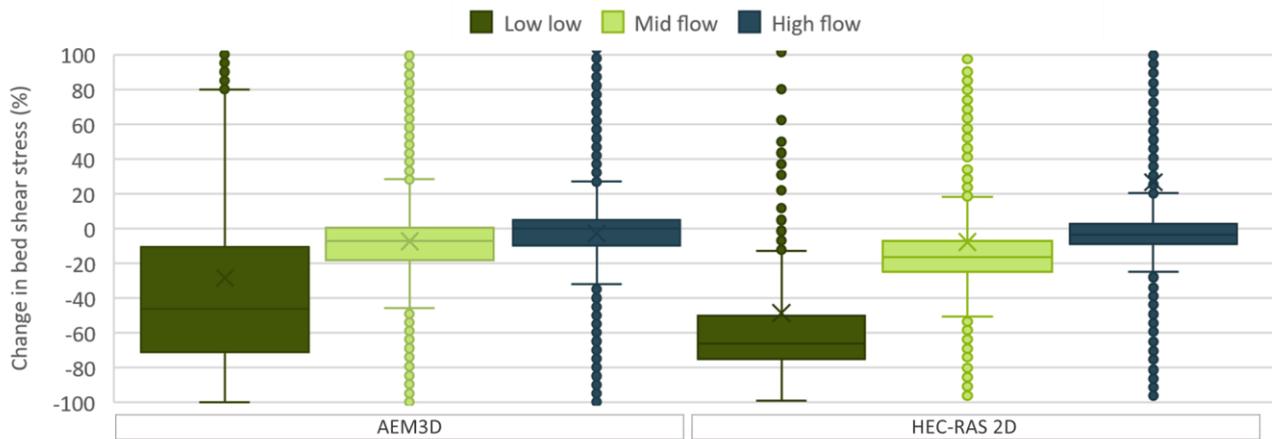
variability in results. The 3D results also showed slightly lower median reduction in bed shear stress for both mid and high flow scenarios.



**Figure 3. Percentage change in bed shear stress between existing pile field scenario and no pile field scenario for the three flows simulated in AEM3D (first row) and HEC-RAS 2D (second row).** As indicated, blue/green shades represent a reduction in bed shear stress due to pile fields, whereas yellow/orange shades indicate an increase.

### Discussion

As expected, modelling indicates that the pile field groynes are more effective during low (frequent) flow events when the pile fields are fully engaged (i.e. not overtopped). Qualitatively, spatial distribution of the shear stress reduction suggests that the 3D model more accurately simulates flow separation, and energy loss, due to the pile fields (indicated as length-wise bands of shear stress reduction). Interestingly, the 3D simulations indicate a lesser reduction in bed shear than the 2D model for all flow events. To validate the 3D results field monitoring should be undertaken during a low to moderate flow event.



**Figure 4.** Box plot showing the variation in percentage change in bed shear stress between existing pile field scenario and no pile field scenario for the three flows simulated in AEM3D (left) and HEC-RAS 2D (right). Outliers >100% are not shown in the figure.

A drawback of the 3D approach relative to the 2D modelling was run time of the model (the Mary River Carters 3D grid has 48 million computational cells). As a result, run times for the model are very slow with a realtime:runtime ratio of 0.01. Run time influenced the vertical resolution (0.5 m) applied in this study. This work will be extended in future studies through the application of a finer vertical resolution at smaller pile field sites to better capture fine scale flow patterns generated by the pile fields.

We have demonstrated that these 3D modelling techniques can be employed to model and enumerate reductions in near-bank shear stress across the length of pile field groyne works. This modelling approach can be used to determine an approximate range of bed shear stress reduction provided by a given pile field configuration. River engineers and river managers can then assess near-bank shear stress under existing conditions and determine the preferred pile configuration to meet the critical shear stress threshold of a specific boundary layer (i.e. structurally diverse vegetation). Furthermore, the influence of different geomorphic conditions can be explored through employing the same analysis at other sites, to allow prediction of pile field performance under various conditions.

### Limitations and future work

Several 3D hydrodynamic models were trialed in this study including NaysCUBE, PHOENICS and AEM3D. The NaysCUBE 3D model, a 3D solver for river flow and bed morphodynamics, was initially trialed. However, we were unable to run simulations with the required grid generation (fine enough resolution) to model flow dynamics through the pile fields. The feasibility of using the PHOENICS CFD model for simulating a region adjacent to the pile field was then investigated. PHOENIC was found appropriate for modelling flow around a single pile field, however it was too computationally intensive over a stretch of river (i.e. at reach scale). Finally, this study investigated whether AEM3D, which is suitable at a reach scale (and designed to simulate at spatial scales of meters to kilometers, and timescales of days to years) can be applied at a finer spatial scale and timescale. To validate the suitability of AEM3D in modelling pile fields, field monitoring is recommended. Future work should also trial other 3D modelling packages.

Limitations of the study include that the AEM3D model is unable to explicitly simulate surface drag induced by the piles, as it uses a no-slip boundary condition on vertical grid faces and the cylindrical shape of the piles is not captured by the grid. Therefore, the model does not account for all energy losses, and the hydraulic performance of the pile fields (in terms of shear stress reduction) is likely not fully captured.

In future studies the alternative pile field configurations will be modelled at the Mary River Carters study site to assess the impact on shear stress reduction. In addition, the study will be applied to several sites across GBR catchments. Several existing pile field restoration sites, with unique hydro-geomorphic characteristics (e.g. channel width, radius of curvature, bank height, and sediment regime), have been identified for use as subjects of future studies, to exemplify the impact of a range parameters on the hydraulic effectiveness of pile field

groynes. These studies will also investigate the hydraulic impact of variation in additional design elements (not explored at the Mary Carters site) such as groyne length past toe of bank (into channel), groyne angle, and groyne tail length and angle.

Results from the 3D modelling approach, in the broader study, will be compared to 2D hydraulic modelling (the typical tool used by river engineers). The 2D modelling will then be iteratively modified with the aim of replicating the hydraulic results produced in the more detailed 3D modelling approach. This process will help develop more accurate approaches for modelling pile field groynes in 2D hydrodynamic modelling.

These assessments will inform the development of design guidelines which assist designers in understanding the potential impacts of pile field groynes on river hydraulics and sediment transport processes. Ultimately, this will assist in optimising the design and installation of pile field groynes, resulting in more cost-effective design approaches for sediment reduction programs within GBR catchments.

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