Rules of reengagement: integrating geomorphology into river diversion designs.

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Key Points

- River diversions are common around mine sites in Australia
- Best practice guidelines suggest that such diversions should be designed to be sympathetic to stream geomorphology
- Diversions around open-cut, iron-ore mines in the Pilbara of WA are frequently carried out despite a poor understanding of the geomorphology of regional watercourses to guide them.
- An investigation of the geomorphology of headwater channels in the Pilbara identified that they have a wide variety of forms driven by diverse underlying processes
- Using hydrodynamic modelling we developed a series of hydraulic criteria to guide diversion design for distinct river reach types.
- Where these hydraulic criteria are achieved, it is likely that channels will establish vegetation and replicate local sediment transport patterns.

Abstract

There are many river diversions around mining pits in Australia. Poor performance of these diversions has led to stricter guidelines for their design, including better appreciation of geomorphic context. The Pilbara region in Western Australia is an area with many open-pit mines and river diversions. There is a poor understanding of the regional watercourses and limited guidelines for the incorporation of geomorphic and environmental elements into river diversion designs. We developed a series of hydrogeomorphic guidelines for headwater channels in the Eastern Pilbara, Western Australia.

We undertook a large-scale regional geomorphic analysis of headwater streams, before focusing on the variability in river reach form. Using Structure-from-Motion photogrammetry (SfM), the presence and distribution of channel features were mapped. The result was a high resolution ‘recipe’ or classification of features for a river addressing the natural morphology, roughness contribution and character of natural rivers within the Pilbara. Direct rainfall modelling provided appropriate rainfall flood frequency estimation for these small ungauged catchments.

This knowledge was integrated to produce a series of guideline hydraulic criteria for the various headwater channels. These guideline hydraulic criteria can be used to design river diversions, in addition to helping us understand more about the complexity and variability of headwater channels within the Eastern Pilbara. These criteria can also help to set ‘closure criteria’ which specify the conditions that mine owners have to meet to return the mine to public ownership.

Keywords

River restoration, mine closure, rehabilitation, geomorphology, river diversion, river relocation

Introduction

Streams are often diverted around mine-pits to allow mining to proceed (Flatley et al., 2018; Flatley and Markham, 2021). The diverted channels can experience many problems, including heightened erosion. The poor performance of past mine diversions has led to many issues, including a reluctance for government to accept the relinquishment of the mine site when the mining has finished (known as closure). Guidelines to improve diversion design emphasize the importance of understanding the morphology, hydraulics and dynamics of the streams that are being diverted. This study investigates the geomorphology of headwater streams in the Pilbara (WA) to improve design of mine-diversion channels.

Headwater river channels (first-to-third order) are frequently diverted in the Pilbara region to facilitate open pit iron ore mining. Once mining has ceased, the river diversion channel should behave like a natural river channel in order to achieve relinquishment of the mine site. This research took place in the Upper Fortescue catchment in the Pilbara region in Western Australia. This area has many open-pit iron ore mines prompting the diversion of many small to medium river channels. The sedimentological, hydrological, and hydraulic controls of the dryland rivers of the Pilbara have not been widely studied, particularly in smaller catchments in headwater settings. Therefore, there are limited guidelines in which to manage the integration of geomorphic features into river diversion designs.

Incorporating a series of reference stream reaches to identify hydraulic conditions is an alternative to applying generic guidelines for river diversion designs. These can be based on reaches up and downstream of the mine site or from similar nearby channels. The characteristics of the reference reach are used to define the attributes (e.g. sediment type or hydraulic conditions) required in the newly constructed channel (Flatley and Markham, 2021). Additional Australian examples of the reference reach approach for river diversion guidelines are found in leading practice guidelines provided by the State of Queensland in 2002 (White et al., 2014). A series of ACARP research projects also derived hydraulic and geomorphic criteria for the design and rehabilitation of river diversion channels in the Bowen Basin, QLD (White and Hardie, 2000; Hardie and Lucas, 2002; Hardie, 2004; White et al., 2014).

Using the ACARP criteria as a leading practice example, natural headwater channels within the Pilbara were investigated to improve understanding of the target geomorphic characteristics to be developed within river diversion channels. Headwater channels were the focus of the study because they are often diverted. Larger channels are also diverted, but that is a separate study. Firstly, a regional study of headwater channels was carried out to establish a geomorphic classification for headwater channels, identifying channel types, their underlying characteristics and average roughness parameters (expressed as Manning's n). Lastly, two-dimensional hydrodynamic modelling was undertaken to simulate flood flows through the catchments to derive guideline hydraulic criteria (velocity, stream power, shear stress) for each channel type.

Field Location

The Pilbara region is a large arid to semi-arid region of Western Australia. The Upper Fortescue catchment (Figure 1) drains the Hamersley Ranges and consists both of erosional and depositional landscapes, comprising steep sided scarps, gorges, alluvial fans, mesas, plateaus, and inselbergs (Killick et al, 1996). The Hamersley Ranges host the larger drainage basins of the Fortescue and Weeli Wolli creeks that both feed into large alluvial fans along the southern margin of the Fortescue Marshes. The Hamersley Ranges have an orographic effect, with several peaks having an annual rainfall twice that of adjacent flat areas (CSIRO, 2015). The region sits in a transitional location between the Eyrean (central desert) and the southern Torresian (tropical) bioclimatic regions (BHP Billiton, 2013). Because of this positioning, tropical depressions and recurrent cyclonic events comprise most the regions' total rainfall (Charles et al., 2015; Taylor and Kerr, 2014), supplying ephemeral rivers with few annual flow events.

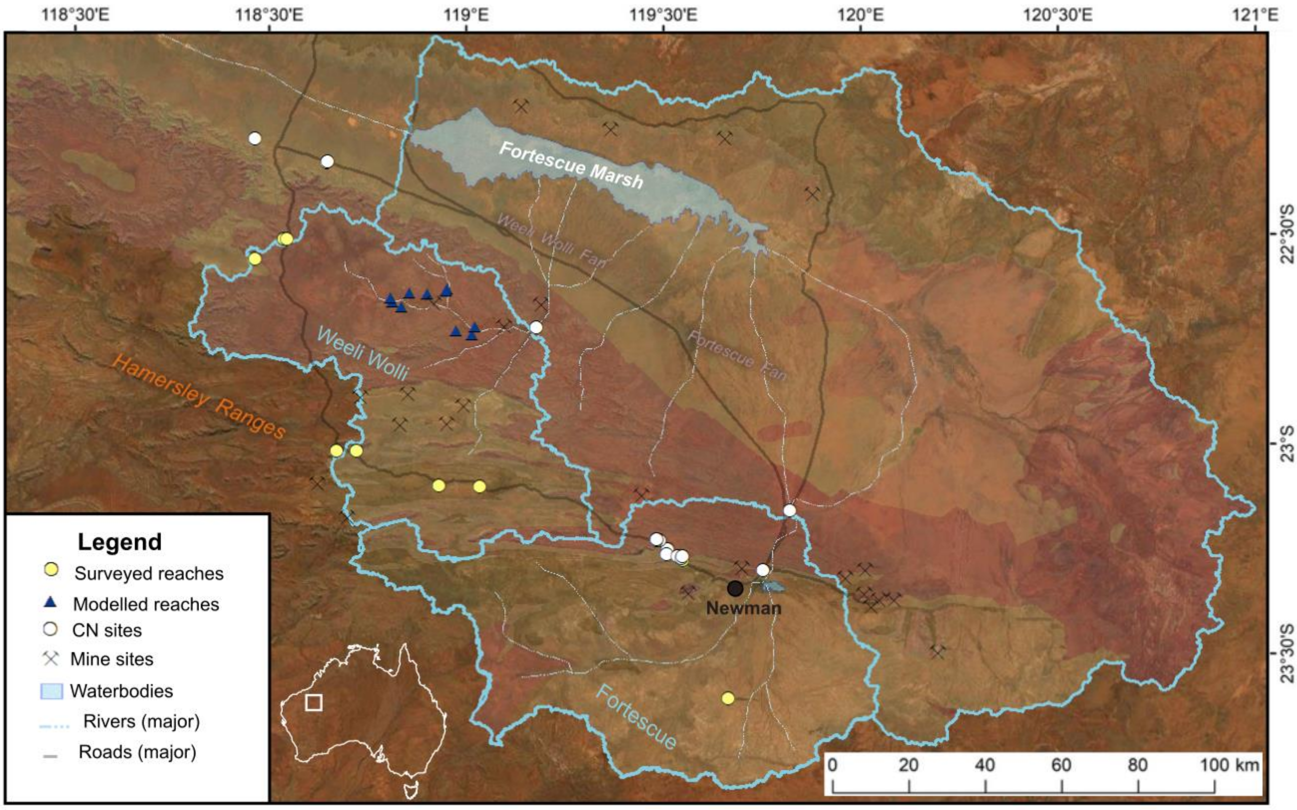


Figure 1. Map of the Upper Fortescue catchment in the Pilbara region, WA. Weeli Wolli and Fortescue sub-catchments and their associated alluvial fans entering Fortescue Marsh are shown. Modelled headwater catchments are shown in navy blue triangles in the Weeli Wolli sub-catchment. CN sites show 10Be/26Al sample locations for the measurement of long-term denudation rates (not reported here).

Methods

The approach of this study was to provide guideline criteria for the development of natural geomorphic and hydraulic characteristics into river diversion designs. A 1m lidar dataset was used to provide a detailed DEM of headwater catchments within the Weeli Wolli sub-catchment in the Upper Fortescue. This dataset was chosen owing to its high resolution and full coverage of the headwater channels. 2D hydrodynamic modelling was undertaken on 10 headwater channels ranging from 0.96 to 6km^2 in catchment size.

Natural channel characteristics

To understand the range of natural channel types, an initial regional scale mapping exercise was undertaken. We used the available spatial data (30m SRTM derived dataset) in addition to a 1m-lidar with a limited extent in the Weeli Wolli sub-catchment surrounding the Yandi mine. The objective of this initial mapping exercise was to create a classification of river channel types in the Pilbara, with a particular focus on headwater channels. This classification was used to group river reaches into recognizable, and quantifiable channel types. Additionally, a centimeter-level accuracy survey was undertaken using Structure-from-motion (SfM) photogrammetry to identify the presence and distribution of channel features within a selection of undisturbed, natural river reaches. The outcome was a series of distinctive reach types that were easily identifiable, with a description of key morphometric characteristics and geomorphic features.

Roughness parameters

From a channel design perspective, incorporating in-channel features provides elements of channel roughness appropriate to the surrounding natural watercourses. In-channel features can reduce flood flow velocities by increasing friction within the channel and subsequently help to maintain sediment continuity and minimize excessive erosion. The absence of such features removes a critical component of channel roughness and hydrogeomorphic variability. Channels were surveyed using Structure-from-Motion (SfM) in conjunction with RTK-GPS total station to create high resolution, accurate pointclouds of river reaches. The dimensions and sedimentological properties of river channels were mapped to quantify characteristic Manning's roughness properties of the river reaches. We used a dataset consisting of 750 cross sections derived from the SfM derived pointclouds. Manning's n values were calculated following Limerinos (1970) after an evaluation of its suitability:

$$n = \frac{(0.8204)\,R^{1/6}}{1.16+2.0\log\left(\frac{R}{d_{84}}\right)} \tag{1}$$

where R is the hydraulic radius of the channel (in meters), d_{84} is the particle diameter (in meters) that equals or exceeds the diameter of 84 percent of the particles. The d_{84} was obtained through precise granulometric analysis of top-view photographs of the channel bed at regular interval, in addition to laser particle sizing of sediments under 1.7mm. The photographs were georeferenced and sediment clasts were measured using BASEGRAIN, an automated MATLAB based object detection software (Detert and Weitbrecht, 2012).

Hydrodynamic modelling

Hydraulic guidelines were created for headwater channels using 2D hydrodynamic modelling in TUFLOW HPC. TUFLOW HPC is a fixed-grid, adaptive time-step hydrodynamic solver that solves the full 2D shallow water equation (BMT, 2018). TUFLOW shows good agreement with other 2D hydrodynamic software (Pasternack and Hopkins, 2017). Headwater catchments in the Pilbara are largely ungauged, lacking measurements of rainfall and streamflow. Prediction of peak flood discharges are commonly ascertained from Regional Flood Frequency Estimates (RFFE). A direct-rainfall model was used to quasi-validate RFFE approaches designed for the Pilbara region to test their suitability for smaller headwater catchments and to select appropriate RFFE methods in the absence of gauged measurements.

We tested 7 RFFE methods derived from preexisting Pilbara gauges or those previously applied successfully in the region. An Index Flood Method (IFM) from Davies and Yip (2014) and Regional Flood Frequency Procedure (RFFP) by Flavell (2012) showed best agreement with the direct-rainfall model and were deemed best suited to small headwater channels. These RFFE approaches were then used to provide peak discharge estimates for a given annual exceedance probability (Table 1). Input rainfall values were obtained from the ARR IFD values. Synthetic hydrographs were created using peak discharge estimates with a time of concentration and hydrographs provided the input for a flow-versus-time (QT) boundary which was applied directly to the 2D domain. The TUFLOW model simulated flow conditions across a 2m-grid catchment representing 5yr, 50yr and 100yr ARI flood events.

Table 1. RFFE Equations used in the development of synthetic flood hydrographs for small headwater catchments in the Pilbara, WA.

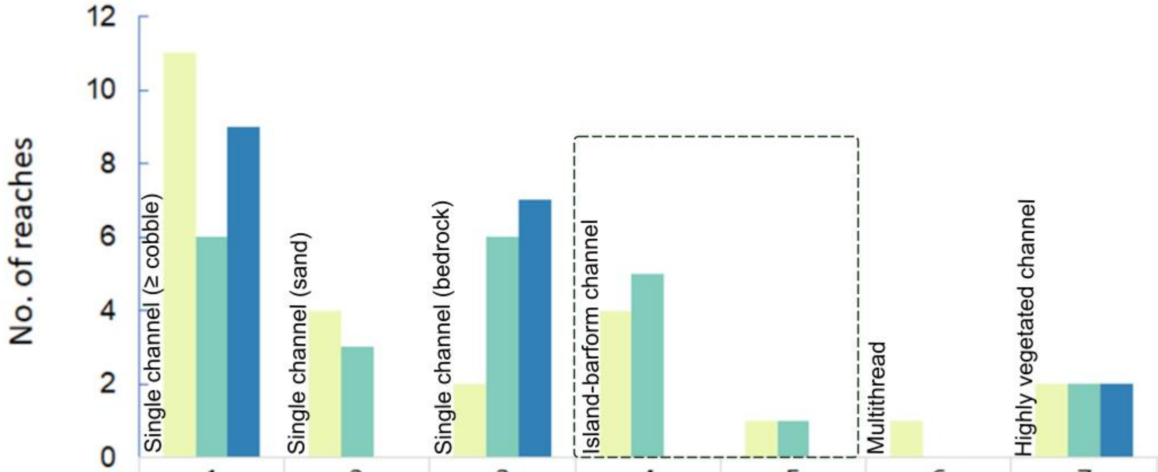
Method	Equation
ARR RFFE Model (2015, 4th Ed)†	$Q_x = Q_{10} \times GF_x$ with Q_{10} as: $\log_{10} = b_0 + b_1 \log_{10}(\text{area}) + b_2 \log_{10}(I_{6,50})$ Where b_0, b_1 and b_2 are regression coefficients, estimated using ordinary least squares (OLS) regression, area is the catchment area in km^2 and $I_{6,50}$ is the design rainfall intensity at catchment centroid for a 6-hour duration and 50% AEP. The values of b_0, b_1 and b_2 and the regional Growth Factors (GFx) are embedded into the RFFE Model.
IFM (Davies and Yip, 2014)	$Q_5 = 7.32 \times 10^{-8} A^{0.651} I_{1hr,\,2yrs}5^{.251}$ Frequency Factors: 2ARI=0.31, 5ARI=1.0 10 ARI=1.70, 20ARI=2.58, 50ARI=4.15, 100ARI=5.82.

RFFP (Flavell, 2012)	$Q_5=7.47 \times 10^{-46}(ASe^{0.5})^{0.81}\, LAT^{-14.62} LONG^{31.40}(L^2/A)^{-0.68}$ With the largest value from each equation being adopted for the Q_{20}. $Q_{50}=Q_{20}$ ×frequency factor (Q_{50}/Q_{20}) $Q_{100}=Q_{20}$ ×frequency factor (Q_{100}/Q^{20}) A = catchment area (km^2), Se = equivalent uniform slope (m/km) and L = mainstream length (km)

† http://rffe.arr-software.org

Results

We firstly present the headwater channel types for our 10 modelled catchments before an overview of how the hydraulic guidelines were created. Discharge, velocity, streampower and bed shear stress values were obtained for 66 cross sections across 10 modelled catchments (Figure 2). Overall, 7 distinct channel types were identified within these confined (27.27% of reaches), semi-confined (34.85% of reaches) and unconfined (37.87% of reaches) geomorphic settings. The 25th and 75th percentile of the output hydraulic values were calculated for each reach type to derive the guideline hydraulic values.



	1	2	3	4	5	6	7
No. Unconfined	11	4	2	4	1	1	2
Semi-Confined	6	3	6	5	1	0	2
Confined	9	0	7	0	0	0	2

Figure 2. Graph showing representative reach types for headwater channels examined in this study. Channel types are distinguished by confinement where reaches are classed as unconfined, semi-confined, or confined. Channel types 1-7 are described in Table 2.

Channel Types

Channel cross sections were characterized into distinct reach types. Single channels were separated into alluvial (cobble or sand-dominant reaches) and bedrock single channels. Multithread (through nascent or island bar forms) channels formed a separate type. Where the channel was heavily vegetated, and the channel substrate could not be clearly seen from aerial imagery, a higher Manning's value was assigned to account for the high contribution of vegetation to channel roughness . The calculated Manning's roughness values are shown in Table 2. Floodplain roughness values (numbers 8-12) were assigned from the Modified Cowan Method (Cowan, 1956).

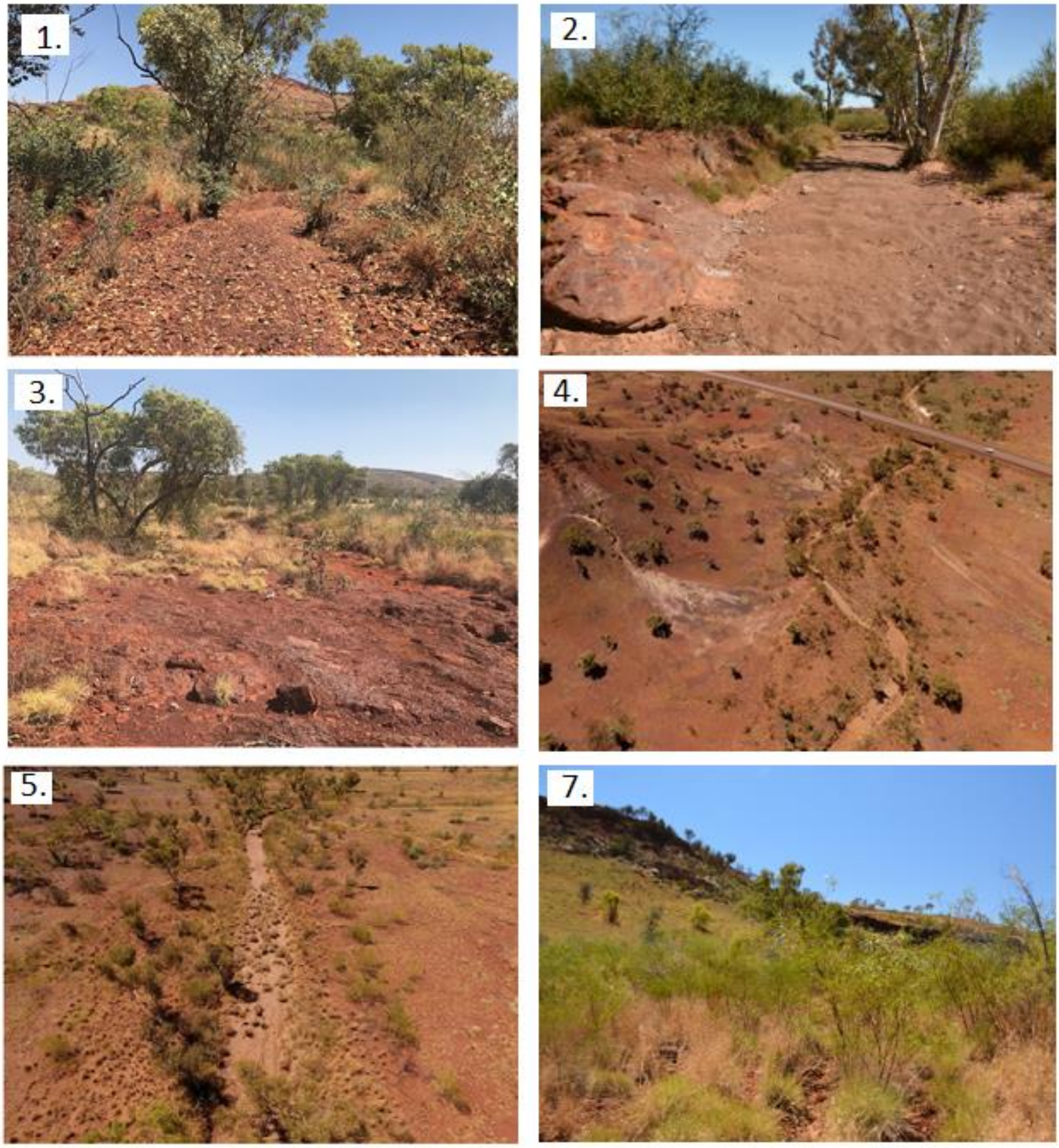


Figure 3. Representative examples of headwater reach types in the Upper Fortescue catchment, WA. 1) Single channel (≥cobble) 2) Single channel (sand), 3) Bedrock 4) Aerial image showing island bar formation 5) Nascent in-channel bars and 7) Highly vegetated channel. For hydraulic guidelines, types 4 and 5 were combined.

Table 2. Channel types of headwater channels in the Pilbara, WA

No.	Channel \ Floodplain Type	Description	Calculated Manning's n
1	Single channel (≥ cobble)	Straight channel with well defined, commonly vegetated banks.	0.043
2	Single channel (sand)	Straight, sandy channel with moderate undulations and sand-dominant bedforms.	0.0274
3	Single channel (bedrock)	Bedrock channel occasionally with a thin veneer of gravels or transported sediments. Thinly vegetated, with large imbricate boulders and cobbles.	0.055
4	Bar (island)	Channel featuring (usually one) stabilized and vegetated island.	0.047
5	Bar (nascent)	Well vegetated section of river channel with nascent (lee or diagonal) bars forming	0.046
6	Multithread	Multithread river channel with two or more well defined river courses	0.038
7	Heavily vegetated channel	Channel is heavily vegetated making remote classification of the channel form unachievable. Vegetation is commonly present across the banks and channel extent.	0.07
8	High floodplain	Well vegetated floodplain	0.035
9	Moderate floodplain	Moderately vegetated channel	0.03
10	Low floodplain	Low vegetation and/or high run-off materials	0.025
11	Road	Sealed or unsealed highway or access roads	0.016
12	Developed/Urban	Infrastructure or construction	0.022

Hydraulic guidelines

Figure 4 shows the average streampower, velocity and basal shear results for channel types. To simplify hydraulic guidelines, channel types with similar hydraulic conditions (e.g., nascent barforms and islands) were grouped.

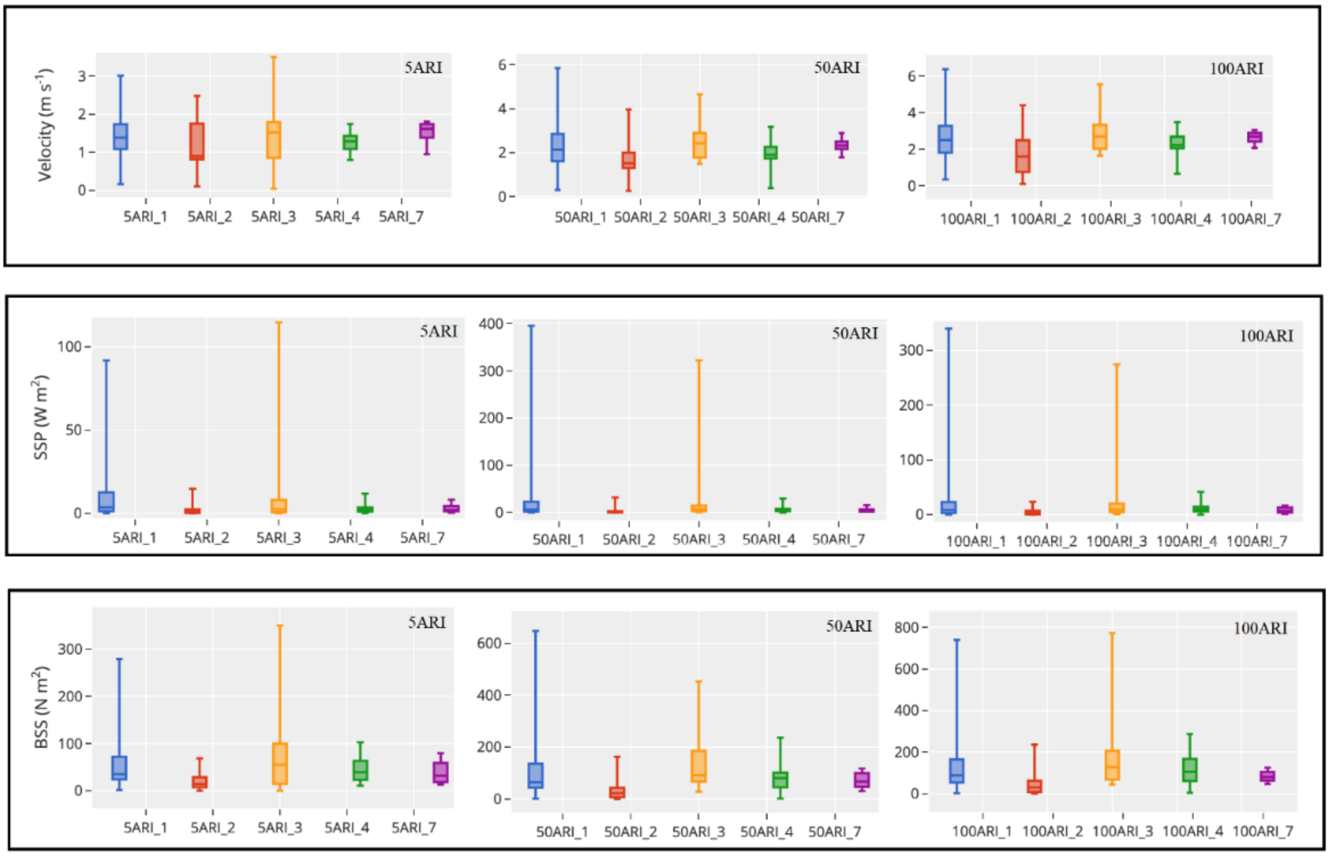


Figure 4. Average velocity, specific stream power (SSP) and basal shear stress (BSS) values are shown for 5 channel types across the 5,50 and 100year average return interval (ARI) flood.

The outcome was a series of guidelines for 5 reach types (Figure 3). These were alluvial single channels (with cobble or sand sediment sizes) bedrock or confined reaches, island-barform channels, and highly vegetated reaches. Hydraulic guidelines for each channel type were calculated from the 25th – 75th percentiles for each cross section based on the average hydraulic results (Table 3).

Table 3. Simplified hydraulic guidelines for headwater channels for floods of 5, 50 and 100yr ARI.

Stream Type	Stream Power (W/m^2)			Velocity (m s^{-1})			Basal shear stress (N/m^2)		
	5AR1	50ARI	100ARI	5ARI	50ARI	100ARI	5ARI	50ARI	100ARI
All headwater channels (combined)	1-6	5-16	6-26	1-2	2-3	2-3	16-72	48-124	50-164
1) Single channel (≥ cobble)	1.3-12.6	1.7-22.3	2.7-22.1	1-1.7	1.6-2.8	1.8-3.3	25.4-69.4	44-135	54-157
2) Single channel (sand)	0.4-2.3	0.2-1.9	0.8-6.4	0.8-1.6	1.35-1.8	0.4-2.0	9.4-22.8	11-38	14-51
3) Bedrock/confined channel	0.9-8	2.9-14.5	5.1-18	0.9-1.8	1.8-2.9	2-3.3	14.9-95.7	70-170	73-200
4) Island/bar channel	1.3-2.9	2.9-7.2	4.3-14	1-1.4	1.8-2.2	2-2.5	24.4-60	52.8-100	50-144
7) Heavily vegetated	1.5-3.1	2.6-6.3	4.2-12	1.5-1.7	2.2-2.5	2.5-2.8	19.7-51.9	63-103	44.95-55.76

Discussion and Conclusions

The use of 2D hydrodynamic modelling allows for the representation of the physical processes and flow conditions that would otherwise be challenging to observe or interpret based on channel form alone. Alongside the creation of guideline hydraulic criteria, interpreting flow events within the headwater channels offered an opportunity to learn more about flood dynamics within these headwater channels. These headwater channels are located in a setting where flow events are sporadic and largely ungauged. Creating distinct channel types and incorporating variable roughness into the flood models allowed for the simulation of realistic flood events for each catchment, helping to identify the variability and variety of these headwater channels.

These suggested guidelines can help engineers and managers design a permanent river diversion that replicates conditions found within local headwater channels. Our results also indicate a wide range of hydraulic values within each channel, highlighting the importance of localized fluctuations in velocity, streampower and basal shear stress. Furthermore, the presence of in-channel features such as nascent bars, islands and vegetation contribute toward the variability of hydraulic values. Additionally, these results show that the existing ACARP criteria for river diversions (commonly used in Queensland but sometimes applied in Western Australia) are not suitable for small headwater channels in the Pilbara, requiring a new industry standard for this region.

These hydraulic guidelines can be used to help drive the design of a final river diversion channel, to create a final landform that is both stable with room for geomorphic processes to occur within their natural range. Additionally, they can be used as a benchmark for existing river diversion channels that may not be performing adequately. For example, the deposition of fine sediment within a river diversion channel can create geomorphic feedbacks with vegetation establishment and continued geomorphic responses. These guidelines show the lower range of SSP required for sand dominant river reaches across all ARI. As such, it is likely that many river diversion channels will not develop sand substrate unless the river diversion dimensions, or subsequent growth of vegetation can dissipate the hydraulic force of flood events.

Hydrodynamic modelling also highlighted the importance of overbank flows and the diversity of the channel-floodplain component within these headwater streams. Even frequently occurring (5ARI) flow events feature overbank flooding owing to the heterogeneity in channel dimensions and stream bank heights as you move downstream. Headwater channels in the Pilbara display a diverse array of geomorphic components that are spatially distributed along the stream profile which help dissipate river flood energy particularly within larger flood flows.

For river diversion channels, this highlights the necessity to consider channel-floodplain interactions for final river diversion designs within these semi-arid channels. Integrating these guideline hydraulic criteria should increase the likelihood of successful vegetation establishment and help the channel develop a characteristic range of geomorphic features. Once mining has ceased, there is more scope to create a channel that is both dynamic and stable. Reengaging the headwater channel with a floodplain for its final landform design will help recreate the overbank flow conditions identified with the flood modelling. However, this will not be feasible in every post-mining environment. However, integrating an appropriate range of hydraulic conditions will increase the likelihood that the river diversion will function as a natural headwater channel. Greater awareness of the reengagement of the channel with its floodplain and associated overbank flows are important in creating long-term stable post-mining landforms.

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