Using Structure-from-Motion Photogrammetry to Improve Roughness Estimates for Headwater Dryland Streams in the Pilbara, Western Australia

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Abstract: There are numerous situations where engineers and managers need to estimate flow resistance (roughness) in natural channels. Most estimates of roughness in small streams come from humid areas. Ephemeral streams in arid and semi-arid areas have different morphology and vegetation that leads to different roughness characteristics, but roughness in this class of stream has seldom been studied. A lack of high-resolution spatial data hinders our understanding of channel form and vegetation composition. High resolution structure-from-motion (SfM)-derived point clouds allow us to estimate channel boundary roughness and quantify the influence of vegetation during bankfull flows. These point clouds show individual plants at centimetre accuracy. Firstly, a semi-supervised machine learning procedure called CANUPO was used to identify and map key geomorphic features within a series of natural channels in the Pilbara region of Western Australia. Secondly, we described the variation within these reaches and the contribution of geomorphic forms and vegetation to the overall in-channel roughness. Channel types are divided into five reach types based on presence and absence of geomorphic forms: bedrock; alluvial single channel (>cobbles or sand dominated; alluvial multithread; composed of either nascent barforms or more established; stable alluvial islands. Using this reach classification as a guide, we present estimates of Manning’s roughness within these channels drawing on an examination of 650 cross sections. The contribution of in-channel vegetation toward increasing channel roughness was investigated at bankfull flow conditions for a subset of reaches. Roughness within these channels is highly variable and established in-channel vegetation can provide between a 35–55% increase in total channel roughness across all channel types. This contribution is likely higher in shallow flows and identifies the importance of integrating vegetation and geomorphic features into restorative practices for these headwater channels. These results also guide Manning’s selection for these semi-arid river systems and contribute to the vegetation-roughness literature within a relatively understudied region.

Keywords: structure-from-motion; river; vegetation; geomorphology; roughness; point cloud

1. Introduction

Ninety percent of Australia’s identified iron ore is mined from the Pilbara region in Western Australia in some of the largest mining sites in the world [1]. Eighty percent of the region’s total iron ore yield is found within the Hamersley Basin, located in the southern part of the Pilbara Craton [2] within the Upper Fortescue Catchment. Headwater rivers in the region are subject to increased pressure from grazing and mining development. Many mines in the Pilbara are intersected by small creeks or rivers and their floodplains. These rivers are frequently diverted to a purpose-built channel to gain access to mineral resources underneath the channel, or to reduce the likelihood of flooding into the surrounding mine. Additional infrastructure servicing these mines, such as railroads and access tracks also disturb these headwater river systems. River diversion is commonly carried out within the...
Pilbara [3] despite a distinct lack of geomorphic research surrounding river systems within the region. Particularly, headwater streams (first-to-third order) have been poorly studied compared with their larger counterparts and consequently, many engineered structures such as culverts and artificial channels are performing poorly.

Artificial river diversion channels within the region have faced issues surrounding their engineering stability, in addition to the ability of the channel to establish natural geomorphic features and vegetation. Work improving the design of river diversion channels in Australia has highlighted the effectiveness of using adjoining reaches as a template for design or the use of alternate prevalent regional stream forms [4,5]. Understanding the natural geomorphology and vegetation conditions of natural river channels within the Pilbara can help establish reference guidelines for artificial river designs. This research provides a better understanding of the types of vegetation patterns within natural channels, in addition to providing guideline roughness values for reach types.

Incorporating elements of channel roughness appropriate for regional watercourses into river diversion designs can offer opportunities to reduce peak flood flow velocities by increasing friction within the channel and minimising excessive erosion [6–8]. Additionally, understanding natural channel roughness can help engineers mitigate against a lack of channel vegetation establishment and improve the development of geomorphic forms and hydrogeomorphic variability. Part of these reference guidelines should identify the relative contributions of in-channel roughness from natural geomorphic features and vegetation. Understanding natural channel roughness can improve current river diversion channels that frequently experience heightened erosion, periodic stripping out of the river channel and an overall lack of vegetation recruitment and geomorphic forms [9].

The derivation and selection of roughness values for natural channels usually requires considerable experience [10] with guidelines for headwater channel usually focusing on perennial river systems [11,12]. Roughness is commonly described by the Manning’s $n$-value. Manning’s $n$ is a frictional loss coefficient that accounts for losses arising from the frictional resistance along the channel boundary, such as the effects of various roughness elements and small-scale irregularities of the boundary [13–15]. It is widely used in many hydrodynamic models to provide a roughness coefficient for conveyance estimation [15]. The presence and variation in material (e.g., sediment, vegetation, and geomorphic forms within the channel) contribute to the overall channel roughness within the river reach and help differentiate between channel types [16]. Dominant factors controlling flow resistance vary longitudinally along the channel network, and in many cases with discharge [16]. As such, many methods to estimate roughness include hydraulic characteristics of the river channel [14,17,18]; however, this is less suitable for the ephemeral rivers within the Pilbara, owing to the lack of streamflow records within the channels. Significant errors in the estimation of discharge can also occur, resulting in discrepancies among Manning’s $n$-values, particularly within low gradient, low roughness channels [19].

Guides for selecting Manning’s coefficients in Australian river channels entirely omit rivers in Western Australia [20], and have few examples of dryland rivers, or headwater channels. Guideline Manning’s estimates for Western Australia apply broad, generalised roughness values [21] that do not fully consider the full diversity of river channel types. There have been few studies addressing the role of channel roughness within Australian dryland rivers [22]. Previous work in Australian drylands have used Limerinos (1970) to estimate the contributions of hydraulic resistance of river red gum (*Eucalyptus camaldulensis*) in ephemeral desert streams [22]. Graeme and Dunkerley (1993) identified the difficulty in obtaining a complete grain size distribution in which to calculate $D_{84}$ within ephemeral streams. However, advances in technological approaches in river channel systems, allow for the improved interpretation of sedimentological attributes within dry riverbeds through advances in structure-from-motion (SfM) approaches, terrestrial lidar scanning, and the improved resolution of digital cameras and associated pixel-based measurement approaches [23].
The goal of this research is to characterise the geomorphology of low-order headwater channels in the Pilbara, WA and establish the hydraulic influence of vegetation during bankfull flows to improve our understanding of the roughness characteristics of dryland ephemeral channels. We applied a semi-supervised machine learning approach to help map the distribution of in-channel features and characterise the boundary conditions within river reaches. Next, we investigated the associated boundary roughness values for the river channels and assess the relative contribution and importance of in-channel vegetation to channel roughness at a bankfull flow depth.

2. Materials and Methods

2.1. Study Area

The Pilbara region is semi-arid, with high temperatures and low annual rainfall [24] dominated by summer storms and occasional cyclonic events. Western Australia is a shield and platform desert landscape occupying an area of relative tectonic stability [25]. The overlying drainage of the Hamersley region within the Pilbara is comprised of dendritic tributaries that drain the higher elevations of the Hamersley and Chichester ranges, supplying the low gradient rivers throughout the Fortescue Catchment. The Hamersley Ranges are underlain by Proterozoic banded iron formation (BIF) which often form caprock or structural benches [26]. Shallow pockets of pisolithic iron are patchily preserved on the summit surface and are interpreted as remnants of a once more extensive regolith [26]. The Hamersley area also features extensive ferricretes, duricrusts cemented with iron found within weathered profiles and sediments [25].

2.2. In-Stream and Riparian Vegetation in the Pilbara

The Pilbara region is known for its high plant diversity (with over 1800 plant species) and highly specialised vegetation arranged in hummock grasslands, tussock grasslands or sclerophyll shrublands [27]. Riparian species cover 4% of the Pilbara region (Figure 1), and 10.5% of the area is composed of groundwater dependent vegetation [28]. Many species in the Pilbara are highly adapted to capitalise on episodic water availability. Common riparian vegetation found within small channels includes river red gum (Eucalyptus camaldulensis), silver-leaved paperbark (Melaleuca argentea) and smooth-barked coolibah (Eucalyptus victrix). The silver-leaved paperbark is an obligate phreatophyte, confined to riparian zones with permanent surface or near surface water and is therefore highly vulnerable to changes in altered surface and groundwater dynamics [29].

River red gum and smooth-barked coolibah is primarily confined to watercourses and river floodplains [30]. Their permanent inundation is rare and typically only occurs in localized areas where groundwater is expressed at the surface [30]. The presence and distribution of riparian vegetation is important for gross primary productivity and ecosystem respiration for isolated pools within headwater streams, and shallow alluvial throughflow influences key ecological processes within these pools [31]. In addition to the ecological importance of riparian vegetation within these channels, riparian vegetation helps to stabilise the channel bed and banks in the river channels. Headwater channels have a notable distribution of small shrubs within and around the channel, such as hard spinifex (Triodia basedowii, T. lanigera, T. longiceps and T. wieana), soft spinifex (Triodia epactia, T. pungens, T. schinzii) and invasive buffel grass (Cenchrus ciliaris) which provide substantial, but somewhat unquantified, in-channel roughness.
with a 1/2.3” CMOS image sensor to capture overlapping imagery (85% frontlap and 65% points [32] to generate high density point clouds. Studies of fluvial geomorphology are point clouds produced for this remote area allow the precise measurement of channel particular study region [14]. A reference reach approach was used to capture the variability (considering the boundary roughness of the channel (width, depth, and sedimentology) and tion of Manning’s geomorphic features in 10 natural channels. Secondly, canopy height models (CHMs) were measured to derive Manning’s roughness values, and coefficients are calculated to cover a broad spectrum of river and stream types to represent the roughness variability in a particular study region [14]. A reference reach approach was used to capture the variability in Manning’s roughness conditions within natural headwater channels. A series of ten headwater channel reaches were surveyed using structure-from-motion (SfM) within the Upper Fortescue Catchment (Figure 2). The high resolution (centimetre level accuracy) point clouds produced for this remote area allow the precise measurement of channel dimensions, geomorphic features, and vegetation. A three-stage approach was undertaken: Firstly, a description of channel types was made using a semi-supervised classification of geomorphic features in 10 natural channels. Secondly, canopy height models (CHMs) were created to measure vegetation parameters in each cross section. Finally, the estimation of Manning’s n roughness contributions for these distinct channel types is made considering the boundary roughness of the channel (width, depth, and sedimentology) and the roughness contribution of in-channel vegetation. These steps are further described below.

2.3. General Approach

The hydraulic properties or boundary conditions in study reaches are commonly measured to derive Manning’s roughness values, and coefficients are calculated to cover a broad spectrum of river and stream types to represent the roughness variability in a particular study region [14]. A reference reach approach was used to capture the variability in Manning’s roughness conditions within natural headwater channels. A series of ten headwater channel reaches were surveyed using structure-from-motion (SfM) within the Upper Fortescue Catchment (Figure 2). The high resolution (centimetre level accuracy) point clouds produced for this remote area allow the precise measurement of channel dimensions, geomorphic features, and vegetation. A three-stage approach was undertaken: Firstly, a description of channel types was made using a semi-supervised classification of geomorphic features in 10 natural channels. Secondly, canopy height models (CHMs) were created to measure vegetation parameters in each cross section. Finally, the estimation of Manning’s n roughness contributions for these distinct channel types is made considering the boundary roughness of the channel (width, depth, and sedimentology) and the roughness contribution of in-channel vegetation. These steps are further described below.

2.4. Fieldwork

SfM photogrammetry employs overlapping images acquired from multiple viewpoints [32] to generate high density point clouds. Studies of fluvial geomorphology are increasingly using airborne remote sensing methodologies to capture the imagery that feeds into SfM algorithms [33], for example the investigation of small-scale geomorphologic change [34], to estimate canopy forest metrics, [35] and as a low-cost alternative for the detection of dominant and co-dominant tree stands [36]. SfM is also used to map and assess large wood accumulations [33] in addition to revolutionising quantitative assessments of river systems [37–40]. We used a DJI Phantom 4 Uncrewed Aerial Vehicle (UAV) equipped with a 1/2.3” CMOS image sensor to capture overlapping imagery (85% frontlap and 65%
sidelap) for 10 natural channels. All imagery was captured at nadir angle (camera looking straight down) at a resolution of 12 MP per image.

Figure 2. Map of surveyed channels in the Upper Fortescue Catchment, in the Pilbara, Western Australia.

A series of spaced ground control points (GCPs) both within the channel of interest and at the survey margins [41], were used to geolocate the final DEM. GCPs consisted of visible tiles measuring 0.5 m \times 0.5 m or fluorescent chalk-based paint spaced closely throughout the survey sites. An RTK-GPS was used to geolocate all GCPs to Australian height datum (AHD) with high absolute accuracies (0.02 m horizontal and 0.04 m vertical). The placing, geolocating, and retrieval of GCPs is the most time-consuming aspect of the survey approach. The use of spray on fluorescent chalk-based paint reduced the overall time that GCP surveying took during the field survey and allowed for frequent placement across the entire survey area. The paint markings will be temporary, remaining visible for the survey period but harmlessly washing away over flood events.

2.5. Point Cloud Processing

Overlapping UAV-derived photos were processed in the Pix4D Mapper Software (Pix4D, SA, Switzerland) to generate a dense point cloud of each river channel. The quality reports, which outline the number, distribution, and relative and absolute accuracies of the dense point cloud and the final DEMs are found in the survey results section. Point clouds were then exported from Pix4D and cleaned in the specialist point cloud processing software CloudCompare using the “Statistical Outlier Removal-SOR” plugin, and the segment tool to remove stray points from the dataset. This step is necessary when point clouds have irregular points due to imagery capturing the horizon, propeller interference or birds. Removal of these erroneous points prevents the final DEM form being artificially warped.

2.5.1. Geomorphic Classification

The variation in channel form and the contribution of geomorphic features to in-channel roughness were assessed using a semi-supervised classification approach. Geomorphic features were mapped and classified into (1) vegetation/non-vegetation, (2) bedrock/non-bedrock, (3) boulder/non-boulder, (4) sand/non-sand, (5) large woody
debris (LWD)/non-LWD, (6) channel bar/non-channel bar. These classes represent the dominant features found within the headwater channels and are responsible for the alteration of hydraulic conditions within the channel and contribute to the overall distribution of channel roughness. Additionally, surveyed river reaches were broadly categorised into channel types based on their confinement, substrate and whether they had a single, island-form or multi-thread planform. The additional geomorphic features were mapped to determine channel type through their presence of absence within each channel cross section (Table 1).

Table 1. Geomorphic features associated with defined channel types.

| Channel Type          | Features Present                | Features Absent                      |
|-----------------------|---------------------------------|--------------------------------------|
| Single channel        | Vegetation, boulders, LWD       | Sand, bedrock, channel bar           |
| Single channel (sand) | Vegetation, sand                 | Bedrock, channel bar, LWD, boulder   |
| Single bedrock        | Bedrock, vegetation,            | Sand, channel bar, LWD, boulder      |
| Bar (island)          | Vegetation, boulders, sand,     | Bedrock                              |
| Bar (Nascent)         | Vegetation, channel bar, LWD,   | Bedrock                              |
|                       | boulder, sand                    |                                      |
| Multithread           | Vegetation, LWD, sand,           | Bedrock, boulder, channel bar        |

We manually tagged groups of points corresponding to geomorphic features (e.g., sediment, vegetation, and exposed rock) in each point cloud and then used the tagged data to train a semi-supervised machine learning model (CANUPO) to classify the entire point cloud. CANUPO was used to first identify and quantify the presence of in-channel features within the headwater channels and secondly the presence of classified features was then used to help determine channel type. For example, where channels were in transition between a cobble substrate and a sand substrate, CANUPO helped quantify the distribution of sediment along a longitudinal profile.

CANUPO uses the geometric properties (multi-scale dimensionality criterion) of the point clouds to distinguish select elements in the scene (such as vegetation, gravel, or bedrock) [42]. Dimensionality refers to how much 1D, 2D, or 3D a subset of points are at various scales (e.g., 1 cm, 10 cm, 20 cm, up to 1 m). Shapes are differentiated based on the dimensionality values at each scale. From the assigned signature of these elements, CANUPO can discriminate these objects from the point cloud allowing for the quick classification of a dense point cloud through semi-supervised computer learning.

CANUPO was selected over other possible classification algorithms because it uses a multi-scale approach and can be easily implemented as a plugin tool in CloudCompare. Additionally, it is not a ‘Black Box’ type model (which aids interpretation) and has been shown to accurately and efficiently classify point clouds for debris distribution patterns of active cliff talus systems [43], to eliminate noise and incorrectly sensed points in snow cover ablation maps [44] for tree and vegetation species mapping [45] and to measure the impacts of floods and landslides on meandering bedrock rivers [46].

To carry out a classification, elements of interest were manually selected from the point cloud in order to create and train a classifier file. The classifier file dictates a binary classification (e.g., assigned vegetation and assigned non-vegetation). CANUPO can be used to create multiple classes within a scene if the files are applied sequentially to non-detected (i.e., assigned non-vegetated points). The classifier files are created through the analysis of a small point cloud sample before applied to a larger point cloud for full classification. The full multi-class classifier files were created from one surveyed river point cloud before being applied to the other point clouds. The end result was a clear indication
of roughness contributors in each channel type based on the high-resolution analysis of the point clouds. The full procedure is illustrated in Figure 3.

![Data collection with UAV in river channel](image1)
![Prepared and cleaned raw point cloud](image2)
![Point cloud sampled for each class](image3)
![Training classifier using dimensionality parameter](image4)
![Apply binary classifier to whole point cloud](image5)
![Confidence estimates mapped for each classification](image6)

**Figure 3.** CANUPO procedure diagram. (a) Data collection from UAV, (b) dense point cloud of river reach, (c) classes are discriminated in the point cloud and partitioned. (d) Classes are defined to create a classifier file, where points are discriminated using dimensionality parameters across a defined series of scales to decide “class one” or “class two,” (e) classifier file is then applied to a whole point cloud, (f) confidence estimate is mapped for the classification to show areas of high and low confidence.

### 2.5.2. Classifier Training

Natural scenes exhibit a large range of characteristic scales and natural features within a given class can have a large degree of geometric heterogeneity (e.g., sediment or vegetation) [42]. Therefore, a combination of scales improves the separability of classes compared...
with a single scale analysis. Each class is represented as a sphere in the plane of maximal separability (Figure 4). The dividing line between the spheres represents the classification boundary between the classes. A clean division between spheres represents a more effective categorisation of classes. The classifier trainer provides an output result to identify the amount of points classified correctly, in addition to statistical output to show distance to the boundary (and standard deviation) alongside balanced accuracy ($ba$) and a value for the Fisher Discriminant Ratio ($fdr$). Balanced accuracy is a measure of the percentage of points truly classified into each class where a high $ba$ value indicates a good recognition rate of a classifier on a given dataset. The $fdr$ is a measure of the class separability and a large $fdr$ value implies a good separation between classes [47]. The output of the classifier maps was used to methodically assign channel types to each cross section based on the classification of channel features.

**Figure 4.** Semi-supervised classifier training result for identified features within natural channels. Data are projected in the plane of maximal separability and the spheres represent each class in the plane of maximal separability. The classification boundary is represented by magenta line and the core points extracted from the point cloud are shown. Greater point mixing between this line indicates a poorer performing classifier file. Class 1 shows vegetation and non-vegetation, a strong performing classifier file with little overlap between the classification boundary.

2.5.3. CHM

Canopy height models (CHMs) were produced for each surveyed river reach to provide an accurate representation of vegetation within and surrounding the river channels. Each surveyed site was divided into equal segments representing a 10 m stretch of channel. Cross sections were delineated digitally across each channel at a 10 m spacing. A 5 m buffer zone was created around each cross section using the ArcMap Buffer function. The point cloud file was then extracted from each buffer zone to create an individual plot cross section. Each cross section was provided a unique plot ID number. A dataset of 750 cross sections was derived from the point clouds. Ground points were delineated for the point clouds and points above the ground surface were calculated and normalised using LAStools using LasGround and LasHeight [48]. Individual CHMs were produced for each cross section using the LAScanopy tool from LAStools. LAScanopy is a tool that computes common forestry metrics from height normalised point clouds [48]. CHMs were produced for vegetation above 0.1 m and canopy metrics (max, min, standard deviation, and density) were obtained for each cross section. Figure 5 shows this procedure. The CHMs were used to assess the contribution of vegetation to total channel roughness.
Phillips and Ingersoll (1998) developed an equation to validate using 37 points from 14 rivers and canal reaches in AZ, USA where $D_{50}$ ranges from 4.6 to 1181 mm. The roughness coefficient ($n$) can be determined by:

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

where $R$ is the hydraulic radius (in meters), $D_{84}$ is the particle diameter (in meters) that equals or exceeds the diameter of 84% of the particles (determined from a sample of about 100 randomly distributed particles). Phillips and Ingersoll (1998) developed an equation to determine Manning’s $n$ for ephemeral streams in arid to semi-arid climates. The equation was validated using 37 points from 14 rivers and canal reaches in AZ, USA where $D_{50}$ ranges from 4.6 to 1181 mm. The roughness coefficient ($n$) can be determined by:

$$n = \frac{0.0926 \left(\frac{R}{D_{50}}\right)^{1/6}}{1.46 + 2.33\log\left(\frac{R}{D_{50}}\right)} \quad (2)$$

where $R$ is the hydraulic radius (in feet) of the channel and $D_{50}$ is the median grain size diameter (in feet). The hydraulic radius of the channel was calculated from the point cloud at known points. We compared the results of Manning’s roughness calculations derived from Limerinos’s (1970) methodology and that of Phillips and Ingersoll (1998) to provide quantified Manning’s values for the headwater channels.

Figure 5. Process of creating CHMs at each cross section. First the cross sections are defined, buffer zones are created around each cross section and given a unique ID, then the point clouds are clipped around each buffer to create these unique CHMs at each cross section.

2.6. Approaches to Estimating Manning’s $n$-Values

We used the high-resolution point cloud data to estimate Manning’s roughness values within the surveyed river reaches. Point clouds were processed in Pix4D and converted into DEMs. Cross sectional data were extracted at each channel 5 m buffer zone from the DEM to provide geometric, hydraulic, and sediment transport parameters. We tested two key approaches to estimate Manning’s $n$-values within arid and semi-arid settings. These were the Phillips and Ingersoll (1998) and Limerinos (1970) approaches. We tested the applicability of these approaches for our low-order channels to expand on this work to consider smaller ephemeral river channels. Limerinos (1970) derived an equation using the Darcy Weisbach friction factor ($f$) to the texture of the bed material, represented by the $D_{84}$ in relation to the hydraulic radius of the channel:
2.7. Sedimentology

Quadrats were used to make a non-invasive measurement of sedimentology and minor morphological changes throughout the reaches. This was combined with several grab samples of sediments of sand size fraction or smaller. The use of sediment quadrats is effective in measuring changes in the size of surface sediments, allowing both the detection of coarsening and fining sequences, average and maximum size of the sediment, allowing the mapping, size classification and establishment of a surface state [49]. At each cross section, precise quantification of sedimentological conditions upon both the bed and bank were carried out. A laser particle sizer (LPS) analysis was used for a selection of grab samples. Quadrats were photographed and georeferenced in the field and the photographs were analysed using BASEGRAIN, an automated MATLAB-based object detection software tool for granulometric analysis of top-view photographs of non-cohesive fluvial gravel beds (sediments over 2 mm) [50,51]. BASEGRAIN calculates the grain size distribution (GSD) of the surface layer using a line-sampling method and estimates the subsurface layer values using a Fuller Distribution (Figure 6) [52]. The BASEGRAIN software was verified [53] and the result output can be used to identify the $D_{50}$ (representing the median grain size) and $D_{84}$ (percentile used to represent the coarse fraction) from vertical images, in addition to providing the cumulative grain size distribution for each sampled location.

![Figure 6. BASEGRAIN software images (a) shows the raw image input and (b) shows the detection of intermediate and long axis. Sediment clasts that intersect the analysis frame are darkened here and removed from the measurement.](image)

2.8. Contribution of Vegetation to Channel Roughness

We used the equation derived by Petryk and Bosmajian (1975) to quantify the contribution of in-channel vegetation to channel roughness [54]. This follows the success of this approach for other larger Australian ephemeral river channels to quantify the roughness contributions of river red gum [22]. Petryk and Bosmajian (1975) estimate Manning’s $n$-values incorporating vegetation drag by obtaining a value relating to boundary roughness (abbreviated as $n_b$) and is determined by:

$$n = n_b \sqrt{1 + \frac{C_d \sum A_i}{2 \sqrt{g AL} \left( \frac{1}{n_b} \right)^2}} R^{4/3}$$  \hspace{1cm} (3)

where $C_d$ is a drag coefficient for the vegetation, $g$ is the acceleration due to gravity (9.81 m/s$^2$), $A_i$ is the stream-wide projected area of the plant lying below the water surface, $A$ is channel cross sectional area, $R$ is the hydraulic radius, and $L$ is the length of the channel reach.

SFM-derived point clouds were used to provide an accurate survey of both ground and non-ground points (Figure 7). We applied the Petryk and Bosmajian (1975) equation to a subset of point clouds from each surveyed channel. We selected cross sections that displayed a variety of vegetation types and distributions within the channel. We focused on
woody, dense, and rigid vegetation where the flow events would not lay over the vegetation, making its contribution to roughness negligible [23]. Additionally, cross sections were selected to include the range of variability of channel characteristics. Transitional areas, of those with tributary junctions or prominent anthropogenic disturbance were avoided. The stream-wide projected area of the plant lying below the surface water was calculated by using the pointpicking tool in CloudCompare by measuring the distance between points in the point cloud. Using this tool, we measured the area of submerged vegetation within the channel ($A_i$). The selection of two points within the point cloud provides segment information between two or more selected points which provides distance or area (see Supplementary Material for more details on this process).

$$n = n_0 + C_d \sum A_i g A L \left( \frac{1}{n-1} \right)$$

where $C_d$ is a drag coefficient for the vegetation, $g$ is the acceleration due to gravity (9.81 m/s), $A_i$ is the stream-wide projected area of the plant lying below the water surface, $A$ is channel cross sectional area, $R$ is the hydraulic radius, and $L$ is the length of the channel reach.

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Figure 7. Illustration showing the point cloud processing steps for the estimation of the contribution of vegetation to channel roughness (using an equation from Petryk and Bosmajian, 1975). (a) shows a processed point cloud of the river reach with geomorphic features identified, (b) highlights the delineation of cross section and (c) shows the extraction of vegetation along the cross section.

3. Results

3.1. Survey Results

The SfM approach yielded accurate point clouds of the streams (Table 2). RMSE values (the standard deviation of prediction errors) were lowest in tributaries with the least vegetation which also facilitated greater GCP placement. Densely vegetated channels (e.g., Homestead 2) experienced larger associated surveying-position error, expressed as Root Mean Square Error (m), most commonly in the vertical direction (RMSEz). In several catchments no GCP tiles were placed (Auski, Unburnt, Meekatharra, Karijini) and therefore no RMSEz value was computed. However, the point clouds were deemed suitable owing to the good agreement between point cloud-derived cross sections and RTK-GPS-surveyed
cross sections. A total of 750 cross sections were extracted from the point clouds, with 697 cross sections deemed suitable for use in this investigation. The other cross sections were discarded due to high survey errors (e.g., high RMSEz), a high level of point cloud noise or too much vegetation making the channel boundary indistinguishable.

Table 2. SfM survey accuracy for catchments.

| Reach        | Survey Area (km²) | Sampling Distance (cm) | Point Density (per m³) | RMSEz (m) | GCP Total |
|--------------|-------------------|------------------------|------------------------|-----------|-----------|
| Amphitheatre | 0.018             | 0.89                   | 3011.18                | 0.065     | 19        |
| Auski        | 0.026             | 0.73                   | 792.4                  | *         | *         |
| Burnt        | 0.16              | 1.5                    | 664.8                  | 0.035     | 40        |
| Homestead    | 0.29              | 1.89                   | 500.22                 | 0.344     | 12        |
| Karijini     | 0.0532            | 0.89                   | 1861.98                | *         | *         |
| Meekatharra  | 0.06              | 1.2                    | 992.04                 | *         | *         |
| Robinson     | 0.053             | 1.39                   | 890                    | *         | 27        |
| Robinson 2   | 0.027             | 0.78                   | 2187.4                 | 0.058     | 29        |
| Ronnie       | 0.07              | 0.93                   | 1586.65                | 0.056     | 48        |
| Unburnt      | 0.033             | 1.45                   | 637                    | *         | *         |

* no RMSEz calculated.

3.2. Geomorphic Classification

We used a classification approach to group river channels. CANUPO classifiers were made to classify six distinct elements: vegetation, bedrock, boulders sand, LWD channel barforms and the absence of these features. The identification of these features determined both the channel type and dominant roughness contributions within the channel. River channel cross sections were grouped into six channel classes; single channel-cobble (69%), single channel-sand (11.9%), bedrock channels (10.2%), bar-island form (5.3%), bar-nascent form (4.2%), and multithread (1%) depending on the number of points classified as each type. The classification of point clouds allows the visualisation and description of these elements within each channel type. The success of the classification of these elements is quantified by a balanced accuracy value ($ba$). Balanced accuracy is a measure of the percentage of points truly classified into each class. Where a high $ba$ value indicates a good recognition rate of a classifier on a given dataset [47]. The Fisher Discriminant Ratio ($fdr$) is a measure of the class separability and a large $fdr$ value implies a good separation between classes [47]. Table 3 shows the results for the geomorphic classification of the point cloud.

Table 3. Results for the geomorphic classification of natural channels. Values show the results of classifier files for a subset of 10,000 point cloud points.

| Class Type      | # | Truly Classified (%) | Falsey Classified (%) | $ba$     | Distance to Boundary | $fdr$  |
|-----------------|---|----------------------|-----------------------|---------|----------------------|--------|
| Vegetated       |   | 70                   | 30                    | 0.958   | −7.590 ± 4.568       | 6.30   |
| Non-vegetated   | 10| 95                   | 5                     | 5.964 ± 2.880 |                  |        |
| Bedrock         |   | 86                   | 14                    | −1.441 ± 1.677 |                  | 0.89   |
| Non-bedrock     | 10| 66                   | 34                    | 2.074 ± 3.320 |                  |        |
| Boulder         |   | 73                   | 27                    | 0.702   | −0.724 ± 1.176       | 0.51   |
| Non-boulder     | 10| 67                   | 33                    | 0.699 ± 1.532 |                  |        |
| Sand            |   | 86                   | 14                    | 1.758 ± 1.640 |                  | 1.41   |
| Non-sand        | 10| 79                   | 21                    | 5.004 ± 5.450 |                  |        |
| LWD             |   | 88                   | 12                    | −2.312 ± 2.012 |                  | 1.15   |
| Non-LWD         | 10| 69                   | 31                    | 0.783   | 0.730 ± 1.994        |        |
| Channel bar     |   | 72                   | 28                    | −0.287 ± 0.660 |                  |        |
| Non-channel bar | 10| 50                   | 50                    | 0.606   | 0.072 ± 0.733        | 0.13   |

Vegetation was the most successfully classified within the point cloud with a high $ba$ value of 0.95 (e.g., 95% classified successfully). Sand was the next most successful feature
being classified within the point cloud with a box value of 0.825 (e.g., 83% success rate). Bedrock, LWD, and boulders were successfully classified 76%, 78%, and 70% respectively. The success of geomorphic feature classification was notably related to the class separability, determined by how different the geomorphic feature was to the surrounding environment. Therefore, vegetation such as trees and distinctive riparian vegetation, in addition to LWD and the distinct geometric shape of sand-bed surface made these features the most readily identifiable. Bedrock, LWD, and boulders had some similar surface attributes making it more challenging to separate these features using our point clouds.

3.3. Channel Roughness

This next section explores the estimation of channel roughness within different surveyed channel types. Table 4 provides a description of surveyed river channel characteristics, and the results from the BASEGRAIN sedimentological analysis to determine average D50, and D84 for each reach type. Surveyed river channel W/D ratios varied between 5.61 and 24.26. Meekatharra has the highest W/D ratio and was the only channel with consistent stable islands with the archetypal anabranching planform as seen in larger river channels in the region. Most channels alternated between reach types (e.g., single thread cobble and nascent barform, and the single thread-sand and single thread-cobble). This can be seen in the standard deviation of the W/D ratio, highlighting how variable the channel form was within each cross section.

Table 4. River reach characteristics as calculated from SfM-derived point clouds and BASEGRAIN sediment analysis. Mean D50 and D84 values from each surveyed channel are shown.

| Channel  | Reach Types                                      | Mean Slope (m/m) | D50 (mm) | D84 (mm) | Mean W/D |
|----------|--------------------------------------------------|------------------|----------|----------|----------|
| Amphitheatre | Alluvial channel (≥cobble or sand) with nascent barforms. | 0.007          | 16.71    | 37.89    | 12.1     |
| Auski     | Unconfined alluvial (≥cobble).                   | 0.014          | 15.38    | 28.52    | 16.94    |
| Burnt     | Unconfined alluvial channel (≥cobble) and nascent barform. | 0.009          | 15.39    | 31.45    | 11.18    |
| Homestead | Unconfined alluvial channel (≥cobble) with stable island forms. | 0.005          | 18.47    | 42.088   | 15.23    |
| Karijini  | Unconfined alluvial channel (≥cobble) and nascent bars. | 0.006          | 14.03    | 26.525   | 16.46    |
| Meekatharra | Unconfined single channel (sand) and stable islands (sand). | 0.003          | 2        | 4        | 24.26    |
| Robinson 1 | Bedrock channel.                                | 0.021          | 21.17    | 58.71    | 12.97    |
| Robinson 2 | Unconfined alluvial channel (sand) and island bars. | 0.014          | 14.16    | 22.414   | 13.04    |
| Ronnie    | Unconfined alluvial (≥cobble) and barforms.     | 0.0025         | 15.49    | 34.77    | 5.61     |
| Unburnt   | Bedrock, alluvial single channel (≥cobble) and barforms. | 0.008          | 126.15   | 8.93     | 8.93     |

Table 5 shows the input roughness values calculated using the Limerinos (1970) equation. The Limerinos-derived values for these headwater channels were similar to field-derived estimates of channel roughness and was therefore deemed suitable for empirical calculations of roughness. There was a surprisingly small deviation from the mean of boundary roughness values for these single thread cobble channels. Bedrock-channel boundary roughness values are high using the Limerinos (1970) equation, and this is due to the highly variable W/D found within the bedrock XS surveyed here, and the large size of sediment (usually cobble-boulder sized) in which to determine a roughness value. Bedrock channels surveyed here were commonly found with a thin blanket of clasts derived from local sources. The Limerinos (1970) method should really be used where the substrate is predominantly alluvial.
Table 5. Manning’s values and W/D ratios for channel types using the Limerinos equation (1970).

| Channel Type         | \( n_{\text{min}} \) | \( n_{\text{max}} \) | Mean \( n \) | Mean W/D |
|----------------------|-----------------------|-----------------------|--------------|----------|
| Single channel (cobble) | 0.0253                | 0.2409                | 0.0427 (±0.015) | 11.731 (±7.695) |
| Single channel (sand)  | 0.0044                | 0.0927                | 0.0274 (±0.023) | 18.604 (±10.788) |
| Single bedrock        | 0.0661                | 0.1757                | 0.0879 (±0.032) | 12.785 (±4.353)  |
| Bar (island)          | 0.0252                | 0.1522                | 0.0474 (±0.022) | 19.679 (±7.679)  |
| Bar (nascent)         | 0.0357                | 0.0893                | 0.0461 (±0.013) | 10.272 (±4.855)  |
| Multithread           | 0.0324                | 0.0447                | 0.0385 (±0.004) | 27.697 (±18.269) |

1 Standard deviation of values are shown in parentheses.

Roughness values for barform island and nascent barform channels are similar. The low standard deviation of roughness values for nascent barform reaches highlights that barforms occur in a very particular channel configuration (where hydraulic and geomorphic values create distinctive conditions for the formation of nascent barforms). The boundary roughness associated with stable island-form features and nascent barforms are comparable and perform a similar role in contributing to channel roughness (particularly within the low flow conditions representative of headwater channels). The Phillips and Ingersoll (1998) equation provided much lower estimates of Manning’s roughness (Table 6). These values are significantly lower than existing guidelines [21] and are not suggested for use in these headwater channels.

Table 6. Manning’s roughness values (n) using Phillips and Ingersoll (1998). Mean difference shows the difference between the Limerinos (1970)-derived average values of channel roughness.

| Channel Type       | \( n_{\text{min}} \) | \( n_{\text{max}} \) | Mean \( n \) | Mean Difference |
|--------------------|-----------------------|-----------------------|--------------|----------------|
| Single channel     | 0.0036                | 0.1431                | 0.0148 (±0.0097) | −0.0279 |
| Single channel (sand) | 0.0024                | 0.0450                | 0.0106 (±0.0085) | −0.0168 |
| Single bedrock     | 0.0231                | 0.0058                | 0.0132 (±0.0044) | −0.0747 |
| Bar (island)       | 0.0220                | 0.0047                | 0.0137 (±0.0043) | −0.0337 |
| Bar (nascent)      | 0.0428                | 0.0428                | 0.0163 (±0.0083) | −0.0298 |
| Multithread        | 0.0057                | 0.0157                | 0.0076 (±0.0036) | −0.0308 |

1 Standard deviation of values are shown in parentheses.

3.4. Vegetation Contribution to Channel Roughness

Table 7 shows the depth averaged contribution of vegetation to channel roughness. We used the Petryk and Bosmajian (1975) equation to calculate the additional roughness contributions from in-channel vegetation at bankfull. The vegetation contribution was calculated for 41 cross sections to encompass all channel types by comparing the channel boundary roughness values derived using Limerinos (1970) to the contribution of vegetation from the Petryk and Bosmajian (1975) equation. Table 8 shows the contribution of the vegetation type grouped into these dominant channel types. Vegetation can provide between a 35–55.6% increase in channel roughness across all channel types. This contribution is calculated for bankfull flows and is likely to be higher in shallow flows owing to the density and distribution of small riparian plants. However, understanding the relative roughness contribution as a basis for estimating Manning’s \( n \)-values is advantageous in the absence of flow gauging data [55]. Figure 8 shows the relative contribution of vegetation across all channel types.
Table 7. Contribution of in-channel vegetation to overall channel roughness in surveyed river reaches.

| Channel XS | Channel Type                      | Limerinos n | Vegetation Contribution n | Change (%) |
|------------|-----------------------------------|-------------|---------------------------|------------|
| Amp XS1    | Confined, alluvial, barform       | 0.04264     | 0.06952                   | +47.93     |
| Amp XS2    | Confined, alluvial sand           | 0.042923    | 0.062041                  | +36.43     |
| Amp XS3    | Semi-confined alluvial, sand      | 0.042933    | 0.06993                   | +47.84     |
| Amp XS4    | Semi-confined alluvial, sand      | 0.0927      | 0.1348                    | +37.01     |
| Amp XS5    | Semi-confined alluvial barform    | 0.0429      | 0.0632                    | +38.27     |
| Burnt XS1  | Unconfined alluvial barform       | 0.0365      | 0.0548                    | +40.09     |
| Burnt XS2  | Unconfined alluvial barform       | 0.0366      | 0.0537                    | +37.87     |
| Burnt XS3  | Unconfined alluvial (cobble)      | 0.0355      | 0.0513                    | +36.41     |
| Burnt XS4  | Unconfined alluvial (cobble)      | 0.0397      | 0.0577                    | +36.96     |
| Burnt XS5  | Unconfined alluvial (cobble)      | 0.0451      | 0.0645                    | +35.40     |
| HS XS1     | Unconfined alluvial (cobble)      | 0.0687      | 0.0947                    | +37.78     |
| HS XS2     | Unconfined alluvial (cobble)      | 0.0697      | 0.0949                    | +36.10     |
| HS XS3     | Unconfined alluvial (cobble)      | 0.0611      | 0.0856                    | +40.16     |
| HS XS4     | Unconfined alluvial, islands      | 0.0454      | 0.0649                    | +35.36     |
| HS XS5     | Unconfined alluvial, islands      | 0.0571      | 0.0821                    | +35.92     |
| HS XS6     | Unconfined alluvial (cobble)      | 0.0550      | 0.0739                    | +34.34     |
| HS XS7     | Unconfined alluvial (cobble)      | 0.0477      | 0.0640                    | +34.23     |
| Karijini XS1 | Unconfined alluvial (cobble)   | 0.0475      | 0.0690                    | +36.91     |
| Karijini XS2 | Unconfined alluvial barform     | 0.0457      | 0.0659                    | +36.20     |
| Karijini XS3 | Unconfined alluvial (cobble)    | 0.0413      | 0.0642                    | +43.41     |
| Meek XS1   | Unconfined alluvial sand barform | 0.00691     | 0.0237                    | +109.70    |
| Meek XS2   | Unconfined alluvial sand barform | 0.00778     | 0.0164                    | +71.30     |
| Meek XS3   | Alluvial single (sand)           | 0.0109      | 0.0187                    | +52.70     |
| Meek XS4   | Alluvial single (sand)           | 0.0104      | 0.0167                    | +46.49     |
| Meek XS5   | Alluvial single (sand)           | 0.0060      | 0.0217                    | +113.36    |
| Robinson 1 XS1 | Bedrock                        | 0.0686      | 0.0991                    | +36.37     |
| Robinson 1 XS2 | Bedrock                        | 0.1234      | 0.1748                    | +34.47     |
| Robinson 1 XS3 | Bedrock                        | 0.0678      | 0.0989                    | +37.31     |
| Robinson 1 XS4 | Bedrock                        | 0.0958      | 0.1391                    | +36.87     |
| Robinson 1 XS5 | Bedrock                        | 0.139       | 0.1979                    | +34.97     |
| Robinson 2 XS1 | Unconfined alluvial (cobble)  | 0.02548     | 0.0382                    | +39.9      |
| Robinson 2 XS2 | Unconfined alluvial (coble)     | 0.0315      | 0.04574                   | +36.87     |
| Robinson 2 XS3 | Unconfined alluvial (coble)     | 0.0298      | 0.0457                    | +42.12     |
| Robinson 2 XS4 | Unconfined alluvial (coble)     | 0.03408     | 0.0501                    | +38.06     |
| Robinson 2 XS5 | Unconfined alluvial (coble)     | 0.0318      | 0.04588                   | +36.25     |
| Robinson 2 XS6 | Unconfined alluvial (coble)     | 0.03682     | 0.05362                   | +37.15     |
| Ronnie XS1 | Unconfined alluvial barform      | 0.0507      | 0.0743                    | +37.76     |
| Ronnie XS2 | Unconfined alluvial (coble)      | 0.0456      | 0.0753                    | +49.13     |
| Ronnie XS3 | Unconfined alluvial (coble)      | 0.0395      | 0.0618                    | +44.03     |
| Ronnie XS4 | Unconfined alluvial (coble)      | 0.0394      | 0.0688                    | +54.34     |
| Ronnie XS5 | Unconfined alluvial (coble)      | 0.0405      | 0.0659                    | +47.74     |

Table 8. Channel type and contribution of vegetation to channel roughness (%).

| Channel Type                      | % Increase in Roughness | Standard Deviation |
|-----------------------------------|-------------------------|--------------------|
| Alluvial single (cobble)          | 38.22                   | 3.50               |
| Alluvial single (sand)            | 55.64                   | 28.99              |
| Nascent barforms                  | 54.48                   | 27.25              |
| Island                            | 35.64                   | *                  |
| Bedrock                           | 35.99                   | 1.23               |

* Only 1 XS measured for this planform and no S.D. was obtained.
Figure 8. Heatmap to show the relative contribution of different vegetation classes to each of the seven channel types. Darker green indicates that a greater proportion of total roughness is derived from the respective vegetation type, lighter green indicates a smaller proportion of total roughness is derived from the respective vegetation class. White indicates no value, where the channel type and associated vegetation pattern was not observed.

Figures 9 and 10 show the longitudinal variation in channel roughness for the surveyed reaches. Plotted above the line graph are the locations where vegetation roughness contributions to channel roughness were calculated. There is a notable longitudinal variation in the channel boundary roughness values that is independent of vegetation contributions. These subtle oscillations of channel roughness occur from upstream to downstream and are attributed to variations in width, depth, and sedimentology within the channel. Amphitheatre, Robinson 2, Robinson 1, and Burnt Creek demonstrate these oscillations in channel roughness, whereas other reaches (Karijini and Homestead 1) display more subtle changes in channel conditions, with the exception of a few localised spikes in channel roughness. Notably, the influence of vegetation upon channel roughness is not readily identified in immediate peaks of roughness. This shows that the channels are dynamic and channel boundary roughness (and the W/D ratio and bedload) has significant control and influence on the total channel roughness. However, the interaction between vegetation-derived roughness and hydraulic boundary roughness is linked through localised flow obstructions and sediment deposition. Future work creating a larger sample set of vegetation measurements can help disentangle this relationship.
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![Figure 9. Longitudinal variations in channel roughness for selected channels.](image)

![Figure 10. Longitudinal variations in channel roughness for selected channels.](image)

4. Discussion

4.1. Deriving Roughness Values

The Limerinos (1970) equation was used to estimate channel roughness. The Phillips and Ingersoll (1998) equation used the $D_{50}$ as a sediment parameter. The median grain size was found to underestimate roughness conditions in arid river channels [22] and this is also the case here with channels in the Pilbara. The Phillips and Ingersoll (1998) roughness equation was developed for arid zone streams in Arizona. However, when applied to channels in the Pilbara, it provided low estimates of Manning's roughness (as shown in Table 5), which were considered small in comparison with the estimates using the Limerinos (1970) equation and the on-site estimation using the Modified Cowan Method. Boundary roughness was considered to be higher than the Phillips and Ingersoll (1998) estimates owing to the composition of the bed and banks, featuring large average grain size within the channel in addition to the abrupt heterogeneity in channel form and the presence and distribution of in-channel features not including vegetation (such as barforms, bank attached bars, islands, and ripples). Estimating roughness values using approaches that include boundary roughness conditions are better suited for rivers in the Pilbara. Boundary conditions are easier to define than approaches that require values from the hydrologic record such as discharge, mean velocity and water surface slope which are typically not available for small headwater streams.

4.2. Role and Importance of Vegetation

The results here show the importance of vegetation and trees to increase channel roughness. Additionally, the information obtained here is useful for the description of river forms in headwater channels in the Pilbara. Vegetation is important in both initiating
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4.2. Role and Importance of Vegetation

The results here show the importance of vegetation and trees to increase channel roughness. Additionally, the information obtained here is useful for the description of river forms in headwater channels in the Pilbara. Vegetation is important in both initiating in-channel heterogeneity and increasing roughness around the channel margin. Alternating roughness within the fluvial domain is not a new phenomenon and is commonly found in fluvial forms (e.g., pool riffle sequences, flow chutes [22,56]). A key motivation for this research is the development of regionally appropriate Manning’s roughness estimates. This is partly so engineers can use these in river diversion designs. Our results indicate that Manning’s roughness values are high, even without vegetation contributions. When estimating the Manning’s roughness value with vegetation, we used the bankfull geometry to assume a flow condition at bankfull. Measurements of the stream-wide projected area of the plant are made to the bankfull height assuming a depth of water equal to the height of the banks. This research suggests that the addition of vegetation provides an increase in channel roughness between 35 and 55.6% compared with a boundary roughness calculation. This demonstrates the importance of both small shrubby vegetation and established trees in reducing erosion and creation geomorphic feedbacks within small semi-arid channels.

The addition of vegetation produced a significant addition to channel roughness. River red gum (Eucalyptus camaldulensis) was demonstrated to provide a substantial increase in roughness within ephemeral desert streams [22] with a percentage increase of 2.3, 14.3, 82.1, 50.0, 64.5, 14.3, and 20.7% across seven study sites. Graeme and Dunkerley (1993) suggested that vegetation may well be the dominant source of roughness in certain Australian desert stream sites. We quantified the roughness contributions of shrubby in-channel vegetation in addition to larger established trees within channels and found that a dense cluster of shrubs can provide as much, or more roughness than large trees (Figure 8) at bankfull flows within headwater channels. Furthermore, shrubs were a significant source of positive feedback through their ability to initiate and stabilise nascent barforms within the channel and contribute to increased channel heterogeneity in reaches that were otherwise straight or reasonably featureless (Figure 11). The relative contribution of vegetation was highest in sand channels, and sand channels with nascent bars. This further supports the idea that vegetation is a dominant source of channel roughness within Australian dryland channels. Our results indicate that this is particularly true for the shallow gradient sand and barform-anabranching type channels characteristic of many low-slope arid Australian
environments with up to 110% change in channel roughness through both tree and shrub position within the channel bed.

Figure 11. Examples of headwater channel surveyed, (a) vegetated headwater channel, (b) nascent in-channel vegetation increasing channel heterogeneity within a straight river reach.

Throughout our analyses of headwater channels in the Pilbara, the unconfined single thread cobble channel was the most common reach type and the relative contribution of vegetation within this channel type was between 35 and 54%. Bedrock XS were least common throughout out survey; however, surprisingly, established vegetation within bedrock channels created the highest Manning’s values within the channels. Bedrock sections were highly localised within survey reaches, but had a flat channel geometry and significant shrubby vegetation. From a channel design perspective, these results show that in addition to vegetation placement, consideration of channel heterogeneity and appropriate addition of coarse bed material is important for creating appropriate roughness parameters. Additionally, once vegetation is included, the roughness values within the channel increase substantially, reiterating the importance of vegetation establishment within artificial channels.

5. Conclusions

The approaches described in this paper enabled the detailed census of in-channel geomorphic features using a quantifiable and repeatable methodology. Machine learning techniques can be applied to identify in-channel geomorphic features to improve our understanding and interpretation of the structure of small headwater channels. Once dominant
channel types were identified, the point clouds were used to estimate boundary channel roughness in addition to a Manning’s roughness value incorporating in-channel vegetation. Ascertaining channel roughness parameters in river corridors is of great importance to achieve an accurate representation of river conditions. Selecting roughness values is commonly ascertained at-a-station, meaning across a cross section and extrapolated across a larger river reach. However, this study reiterates that the distribution of roughness values within a river reach is highly spatially variable. An additional outcome is a series of guideline Manning’s roughness values for different reach types within headwater channels.

The approach of calculating roughness via a dense point cloud can be applied to understand resistance contributions on flow hydraulics within streams and rivers in the absence of gauged flow information. Additionally, this procedure is useful in furthering our understanding of roughness contributions within poorly understood riverine environments and can advance our understanding of the diversity of flow resistance within river channels. This roughness mapping procedure is a replicable approach toward mapping complex and highly spatially variable channel roughness and can easily be applied to determine river conditions in other environments. Understanding geomorphic variability and the underpinning processes within these channels can improve the development of quantitative guidelines and enhance the development of closure criteria for artificial river diversion channels carried out within the region.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/rs14030454/s1, Figure S1: Structure-from-Motion derived point-clouds; Figure S2: Illustration showing the pointcloud processing steps for the estimation of channel boundary roughness; Figure S3: Example of the process of calculating A_i; Table S1: Calculation of A_i, the streamwide projected area of plants lying below the water surface (at bankfull); Table S2: Description of SfM derived vegetation cross sections.

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