Identifying conditions that sculpted bedforms: Human insights to build an effective AI

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Abstract. In a survey, 42 participants could visually recognise which flow conditions created bedforms (e.g. sand dunes, riverbed ripples) from distance-height profiles, particularly if multiple bedforms are present. An interpreter's geoscience expertise does not help whilst only one set of 'training' examples are needed, together indicating that a machine learning algorithm might be trained successfully from limited data especially if it is 'helped' by pre-processing bedforms into a simple shape familiar from childhood play. Preliminary investigations with an artificial neural network confirm these insights, illustrating that a geoscience communication activity can help design an effective Artificial Intelligence or 'AI'.

1 Introduction

Environmental flows shape the surface they flow over. The variety of features produced (e.g. sand ripples on a beach), known as bedforms, reflect and preserve characteristics (e.g. speed, depth) of the flowing ice, water or air (Venditti, 2012; Bullard et al., 2011; Storrar and Stokes, 2007). The relationships between bedform morphology and flow are contested where observation is extremely difficult, such as under ice-sheets (e.g. Clark et al., 2018; Hillier et al., 2018; Rose, 1987; King et al., 2009), and best understood for unidirectional water flow over sand in a laboratory setting, mimicking a river (e.g. Fig. 1a). Even in this idealised fluvial setting, it is difficult to construct a 1-to-1 link between bedform type (e.g. ripples or dunes) and specific flow conditions (Venditti, 2012; Froehlich, 2020). Illustratively, ripples have a higher aspect ratio (H/L, for height (H) and length (L)) than dunes (e.g. Allen, 1968); yet the observational ranges overlap (Venditti, 2012; Yalin, 1972), creating uncertainty when attempting to link morphology with hydraulic conditions. Many variables related to hydraulics and/or the physics of sediment movement have been proposed to remove the overlap in bedform stability diagrams such as Fig. 1a (see Venditti, 2012). Only recently, has a distinct and non-overlapping zonation of bedform type and flow structure been developed using a quantity called shear velocity (Duran Vinet et al., 2019). Inverting this result may help realise the aspiration of developing a means to reliably infer flow conditions from bedform morphology (e.g. Duran Vinet et al., 2019; Venditti, 2012; Myrow et al., 2018), which is often the only option (e.g. sedimentary structures preserving the geological past, Mars)(e.g. Ohata et al., 2017; Edgett and Lancaster, 1993).

Machine learning or 'AI' algorithms, such as Artificial Neural Networks (ANNs) have great potential in geomorphology (e.g. Sofia et al., 2016; Froehlich, 2020; Valentine and Kalnins, 2016; Shumack et al., 2020) and offer an opportunity to examine this problem as they do not assume simple (e.g. linear or 1-to-1) relationships between inputs and predicted variables (Wang et al., 2009; Faruk, 2010). There may be unexploited quantitative morphological subtleties to categorise bedforms, or even to accurately position them on stability diagrams. This work examines the scope for using ANNs to distinguish the flow conditions in which relict bedforms originated by asking if the ability exists in non-artificial (human) intelligence for two particulars:

Q1 - Is it possible to identify the environment (e.g. river, desert) of a bedform's genesis from its shape?
Q2 - In the fluvial environment, is it possible to distinguish flow conditions?

2 Method, Data & Ethics

An online survey was conducted, initially at the '*Non-equilibrium flows and landforms*' workshop (19th May 2021), with participation expanded using authors' close contacts (friends, colleagues, and family). For Q1, participants attributed distance-height profiles across 34 individual bedforms, and 13 bedform sequences (≥3 bedforms) to one of four environments (*fluvial* [river], *glacial*, *marine*, *aeolian* [desert]). For Q2, participants ranked three profiles according to flow strength (shear velocity), thrice for individual forms, and thrice for bedform sequences. Examples were provided to isolate visual shape analysis from prior knowledge (Fig. 1b), black and white profiles were used to exclude contextual clues (e.g. dataset characteristics, other features in the landscape), and the order of options (e.g. B, A, C) was shuffled for each participant to prevent bias. Scale (e.g. metres) readily distinguishes environment without using bedform shape, so it was not given.

Ethical approval was given by the Ethics Review Sub-Committee at Loughborough University.

Aeolian data are ASTER (v2) across linear and transverse dune types from the Namib desert (Bullard et al., 2011), glacial are from near Lough Gara in Ireland (Hillier and Smith, 2008), fluvial are from four laboratory experiments (Expts. 1-4) of non-linearly increasing shear velocity (Unsworth, 2015), and marine data are from the Irish Sea. For consistency, simplicity and accessibility, these varied data are referred to as distance-height profiles, with 'time' equated to 'distance' where strictly necessary. For the survey, representative examples of individual bedforms and sequences were manually selected from these datasets. Pre-processing to estimate bedforms' height (H) and width (W) - see Fig. 1c & d - used the Spatial Wavelet Transform (SWT) algorithm (Hillier, 2008) and fitting of flat-topped cones (Hillier, 2006).

ANN analysis to follow up the survey used a Multi-Layered Perceptron (MLP) with four hidden layers with 28, 56, 56 and 28 nodes, each with a ReLU activation function. In a baseline analysis, input to predict the fluvial flow regime (coded by experiment number) was non-overlapping profile segments 160 seconds long. After this, to 'help' the ANN bedform shapes (H, W) were input once each per analysis, either (i) individually or (ii) as groups of five bedforms in increasing size order, selected at random without replacement. Weights and biases were updated using the Adam Optimiser of PyTorch using a loss function that calculates the Mean Squared Error (MSE), all within a feedforward back-propagation approach.

3 Results

Of the 42 survey participants 25 self-identified as geoscientists, and 16 did not. For Q1, participants correctly identified the one of four environments (e.g. fluvial, aeolian) in which individual features originated 32% of the time, slightly if significantly (2-tailed t-test, $p \ll 0.01$) better than the 25% expected of guesswork. This rises to 51% for bedform sequences. For Q2, participants ranked entirely correctly 3 flow strengths (Expts. 1-3) for 46% of individual features, and 60% of sequences, much better than the 16% expected of guesswork ($p \ll 0.01$).

In none of the questions did geoscientists perform better than non-geoscientists, with mean percentages of correct answers being indistinguishable (2-tailed t-test, $p > 0.05$). The overall sentiment is encapsulated by one comment:

> "*I felt this was a geometrical exercise of recognising same patterns at different scales. I did not feel that my experience as an "expert" in bedforms really made any difference from, say, my son taking the test.*"

Several participants commented that their ability to distinguish environments might be to do with characteristics of the data (e.g. smoothness due to data resolution), not bedform shape. This is a potential pit-fall of training an ANN, avoided here by only analysing the fluvial data.

In the baseline ANN analysis, flow regime was predicted poorly ($r^2 = 0.03$). Visually, individual bedforms' shapes (H, W) overlap between experiments but their trends, and averages over a number of points, are distinctly different (Fig. 1d). This maps directly to results of the ANN (Fig. 1e). Individual forms are weakly predicted (light grey, $r^2 = 0.11$), but sub-sets of 5 bedforms more strongly so (grey, $r^2 = 0.56$), particularly if very small bedforms present in all experiments ($H < 0.5$ cm) are excluded (dark grey, $r^2 = 0.80$).

4 Discussion

Morphologies from differing environments (e.g. glacial, fluvial) can be viewed as similar, indicators of analogous processes at work (e.g. Shaw, 1983), and modelled with identical equations (e.g. Fowler, 2002; Duran Vinet et al., 2019) or statistics (e.g. Hillier et al., 2016; Einstein, 1937). Despite similarities in appearance, the survey results clearly demonstrate a level of ability to distinguish flow conditions from distance-height data of the bed, and imply that an ANN should perform better if utilising sequences of bedforms rather than evaluating individual forms in isolation. Interestingly, geoscientists' *a priori* and contextual knowledge added little, indicating that training an ANN on distance-height data alone should be productive. Furthermore, one training dataset sufficed for the survey's participants, prompting the idea that the requirement to train ANNs performing pure pattern recognition on 1000s of datasets (e.g. Bishop, 1996) might be mitigated by 'helping' the ANN by pre-processing into simple shape parameters that would have been readily understood by all participants (e.g. width). This would be useful as examples in nature are often limited in number.

Preliminary analysis with an ANN (Fig. 1) supports these speculations. It demonstrates that an AI with some level of predictive efficacy can be built, and this improves by using bedform sequences (Fig. 1e). *H* and *W* were selected to 'help' the ANN, although relevant geo-statistical properties (e.g. Malinverno, 1988; Powell et al., 2016; Singh et al., 2011) might have been used instead. The increase in predictive skill from r^2 of 0.03 to 0.80 with pre-processing 'help' demonstrates, in principle, the utility of this approach when building an effective AI for geomorphology. This study was on equilibrium conditions but in the future ANNs may be key to disentangling forms and flow for transitional, non-equilibrium conditions (e.g. see Myrow et al., 2018).

Supporting material

The survey form and anonymised answers are provided for completeness and transparency. For the ANN, input data with associated README file and pseudo-code are provided to make the work reproducible.

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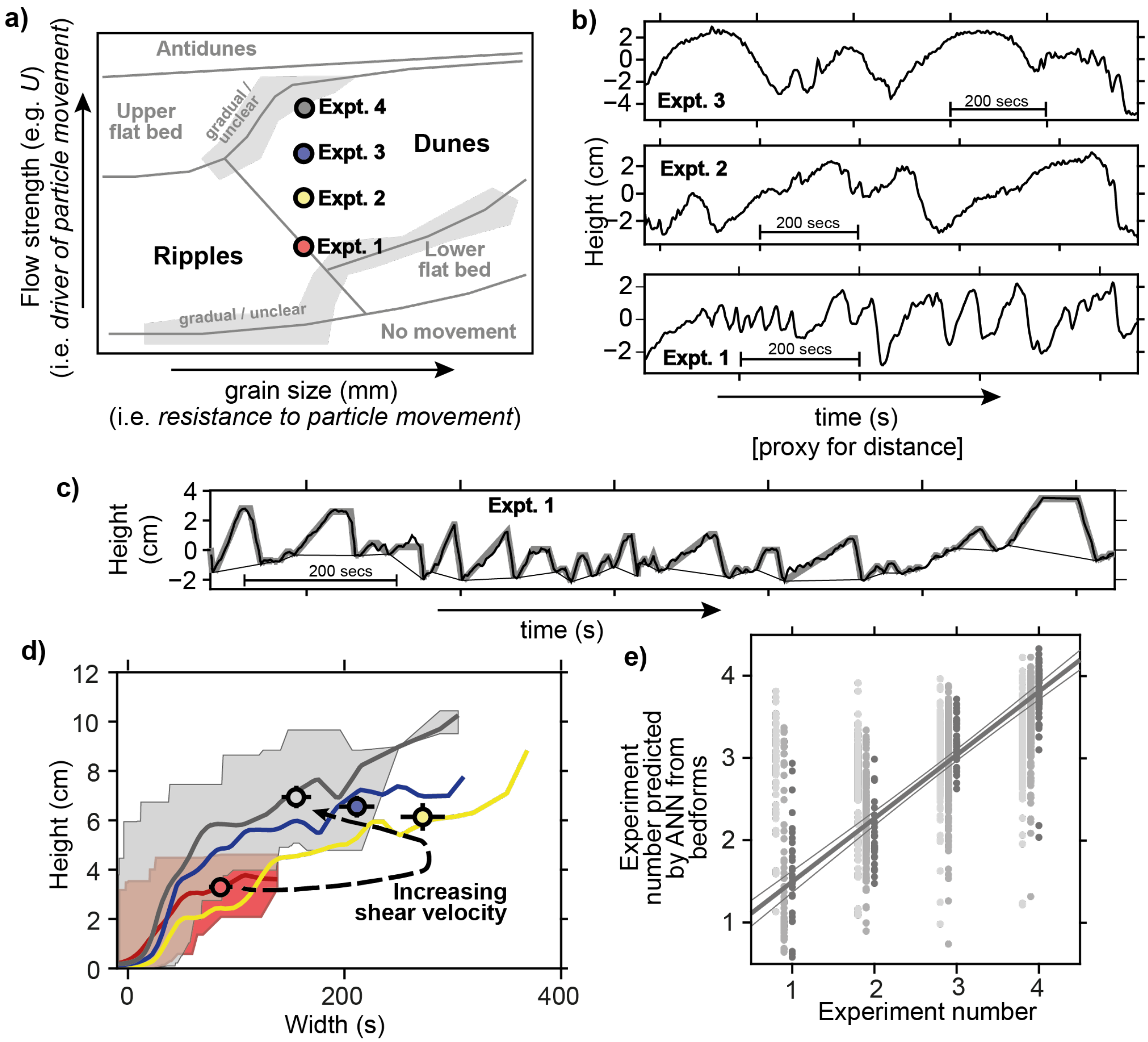

Figure 1: (a) Illustrative bedform stability 'phase diagram' for unidirectional fluvial (i.e. river) bedforms, synthesized from multiple sources (Ohata et al., 2017; Lewis and McConchie, 1994; Southard and Boguchwal, 1990). Main types considered here (i.e. ripples and dunes) are highlighted. Experiments 1-4 are positioned indicatively. (b) Distance-height profiles (strictly speaking time-series) like those given unannotated to participants, i.e. one from each experiment 1-3, all scaled to the same dimensions. Horizontal axis is time because in the flume tank a stationary sensor recorded height as bedforms passed beneath it. (c) Example of how H and W are determined. Measured heights (thick black line) are processed using the SWT algorithm to identify bedforms, drawing a line beneath them (thin black line) then approximated as flat-topped cones (grey lines). SWT parameters as Hillier (2008). (d) Height-width relationships for the 4 experiments, with colours as in (a): lines are sliding means with W (Gaussian weights, width 60), shaded areas are full ranges for Expts. 1 & 4, and dots are the means ($\pm 2\sigma$) of upper quartile of the data when the small bedforms (i.e. $H < 0.5$ cm) are excluded. (e) Comparison of actual experiment number for out of sample prediction by the ANN using H and W: individual bedforms (light grey), subsets of 5 bedforms with (grey) and excluding (dark grey) small bedforms.