



Original software publication

# Bedforms-ATM, an open source software to analyze the scale-based hierarchies and dimensionality of natural bed forms



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## ABSTRACT

Bedforms-ATM (Bed forms analysis toolkit for multiscale modeling) is a software designed to hierarchize and quantify the dimensionality of natural bed forms fields. It comprises four modular applications, namely: (1) wavelet analysis, (2) Hovmöller analysis, (3) multiscale discrimination, and (4) three-dimensionality analysis. Bedforms-ATM also provides insights on bed form systems dynamics and their interrelationship with the surrounding hydrodynamic characteristics. The software structure encourages its expandability via the collaboration from the community of users. Both fluvial and synthetic bed form data accompany Bedforms-ATM.

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## Code metadata

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Permanent link to code/repository used of this code version

Legal Code License

Code versioning system used

Software code languages, tools, and services used

Compilation requirements, operating environments & dependencies

If available Link to developer documentation/manual

Support email for questions

v1.1

<https://sourceforge.net/projects/bedforms-atm/>,

[https://github.com/ElsevierSoftwareX/SOFTX\\_2018\\_28](https://github.com/ElsevierSoftwareX/SOFTX_2018_28)

GNU GPL v3 or later

git

MATLAB

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<https://sourceforge.net/projects/bedforms-atm/>,

<https://github.com/rgutierrez1/BedformsATM>

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## 1. Introduction

Although the need of discriminating bed forms scales (e.g., bars, dunes and ripples) that are commonly present in unidirectional, oscillatory and combined flows has been highlighted by many researchers [e.g. 1–3], no standard nomenclature and procedure exist to systematically identify the scale and magnitude of such sedimentary features [3]. As a result, the discrimination between ripples and dunes is taken as obvious and many authors provide

limited or no explanation regarding the criteria they followed for their discrimination in field and laboratory studies [1]. Reference [3] introduced a spectral–structural technique that allowed for a quantitative characterization of three bed form hierarchies (Fig. 1-a and 1-b) even for curved bed form fields (Fig. 1-c). However, it is not able to differentiate between two dimensional (2D) and three dimensional (3D) bed form features. The structural component of the technique presented by [3] obeys the scale-based classification scheme proposed by [4]. It defines ripples as features having wavelengths less than 0.6 m; dunes as features characterized by wavelength thresholds of 5, 10, and 100 m determining small, medium and large dunes; and bars as features having wavelengths higher than 100 m. The spectral component of the

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technique proposed by [3] is based on the coupled application of robust spline filters and the one dimensional continuous wavelet transforms frame developed by [5].

Bed forms in sedimentary environments are predominantly 3D in planform [3]. This characteristic induces marked differences in local turbulence, drag coefficient, and dispersal patterns of sediments [6–8]. Therefore, a complete bed forms description requires distinguishing between 2D and 3D bed forms. To this end, [9] proposed a quantitative continuum metric, named 3-dimensionality index (3DI), which varies between 0 (strictly 2D) and 1 (strictly 3D). 3DI (cf. Fig. 1) quantifies the normalized autocorrelation between the fluctuations of a bed form field  $\eta(x_i, y_i)$  respect to the local cross-sectional mean  $\bar{\eta}_x(y_i)$ , and the fluctuations of the local stream-wise mean  $\bar{\eta}_y(x_i)$  respect to the bed form field mean  $\bar{\eta}_{xy}$  (Eqs. (1)–(4)). Thus, a strictly 2D bed form has a flat crest perpendicular to the flow, and the more irregular the cross-sectional profiles are, the greater the value of 3DI.

Most computer programs designed to analyze bed forms fields (e.g., Bed form tracking tool by [2]) are not currently publicly available or are discontinued. Herein we present Bedforms-ATM (Bed forms analysis toolkit for multiscale modeling), a MATLAB open source software that performs the variability analysis of bed form fields by quantitatively describing both their hierarchies and dimensionality.

This paper presents the technical aspects of the development and capabilities of Bedforms-ATM and is organized as follows: Section 2 describes the data processing methods used in this study, Section 3 provides a functional description of Bedforms-ATM, Section 4 focuses on its implementation, Section 5 presents case histories of its application on bed forms and synthetic bed forms, and Section 6 discusses on its potential impact. Finally, Section 7 outlines the main conclusions of this study.

## 2. Background

Fig. 1 shows an approximately equally spaced (i.e.,  $\Delta x \approx$  constant) elevation bed form profile  $\eta(x_i, y_j) \in \eta(x_i, y_j)$ , also represented herein by the vector  $\eta^{yJ}(x_i)$ . The software performs the wavelet analysis (Application 1) of each bed form profile in  $\eta(x_i, y_j)$  by adapting the one dimensional continuous wavelet analysis package developed by [5]. The continuous wavelet transform of  $\eta^{yJ}(x_i)$  is mathematically defined as the convolution of it with a continuous wavelet function. By performing a Monte Carlo analysis, [5] estimated empirical factors that allow for determining both the local wavelet power spectrum (i.e., the modulus of the wavelet transform) and its cone of influence (i.e., the divide that discriminates reliable from spurious local power spectrum results). This is done for continuous wavelet functions such as Morlet, Paul, Marr and the derivative of the Gaussian, at a given confidence level. Thus, the spatial distribution of the wavelengths along  $\eta^{yJ}(x_i)$  is obtained. Subsequently, the wavelet spectrum provides information about the dominant constituent wavelengths of  $\eta^{yJ}(x_i)$ . The reader is kindly referred to [5] and [3] for technical details of the application of wavelet transforms on bed forms variability analysis.

Application 2 (power Hovmöller analysis) is an extension of Application 1 [5]. Basically, the Power Hovmöller analysis allows for locating bed form features in  $\eta^{yJ}(x_i)$  that lie in a specific wavelength interval by passing the bed form profile with a continuous-wavelet-based high-pass filter and low-pass filter, which are defined by such interval. Thus, by applying that procedure to each bed form profile in  $\eta(x_i, y_i)$ , the locations of such features are mapped on the bed form field domain [3].

Application 3 (scale-based discrimination) allows for obtaining three hierarchies from  $\eta^{yJ}(x_i)$  by setting two wavelength thresholds,  $\theta_{1,3}$  and  $\theta_{3,3}$ . The smallest scales are comprised in Hierarchy 1, which are determined following the structural criteria presented

by [3]. For instance, if Hierarchy 1 corresponds to ripples,  $\theta_{1,3} = 0.6$  m and if Hierarchy 1 corresponds to small dunes,  $\theta_{1,3} = 5$  m. The largest scales are comprised in Hierarchy 3, and are retrieved from the wavelet spectrum according to a threshold  $\theta_{3,3}$  typically set  $>100$  m. Hierarchy 2 is determined by subtracting scales in Hierarchy 1 and Hierarchy 3 from  $\eta^{yJ}(x_i)$ . A given situation could present more than three scales of interest, i.e ripples, small dunes, intermediate dunes, large dunes, and bars. In such cases, the described procedure would first discriminate ripples, dunes and bars as hierarchies 1, 2 and 3, respectively. Further, the discrimination procedure can be applied again on the intermediate scales in Hierarchy 2, distinguishing small, intermediate and large dunes.

It is important to note that the methods used for Applications 3 are optimized versions of those proposed by [3] in the following aspects: learning curves to allow for an efficient bias–variance trade-off at each hierarchy are used, and the bias–variance error is distributed among them, and thus the discriminated hierarchies are denoised at a better extent. Likewise, when the bed form data is provided as a water depth field (e.g.  $h(x_i, y_j)$  in Fig. 1), the application verifies the expected weak correlation between  $h_{1,3}(x_i, y_i)$ , namely a Hierarchy 1 field, and the mean water depth (e.g.  $\bar{h}_x(y_j)$  in Fig. 1) by using the proxy parameter named scale–variance–ratio (SVR<sub>1,2</sub>) proposed by [3] representing the ratio between the standard deviation of Hierarchy 1 and that of Hierarchy 2. The reader is kindly referred to [3] and the flow diagrams in the User Manual of Bedforms-ATM for details on the methodology of Applications 1, 2, and 3.

The three-dimensionality analysis (Application 4) is performed by using 3DI definition proposed by [9] (Eqs. (1)–(4)).

$$\bar{\eta}_y(x_i) = \frac{\sum_{j=1}^n \eta(x_i, y_j)}{n} \quad (1)$$

$$\bar{\eta}_x(y_i) = \frac{\sum_{i=1}^m \eta(x_i, y_j)}{m} \quad (2)$$

$$\bar{\eta}_{xy} = \frac{\sum_{i=1}^n \sum_{j=1}^m \eta(x_i, y_j)}{m \times n} \quad (3)$$

$$R = \frac{1}{m \times n} \sum_{i=1}^n \sum_{j=1}^m \left[ \left( \frac{\eta(x_i, y_i) - \bar{\eta}_x(y_i)}{\sigma_x(y_i)} \right) \left( \frac{\bar{\eta}_y(x_i) - \bar{\eta}_{xy}}{\sigma_{xy}} \right) \right] \quad (4)$$

where  $\sigma_x(y_i)$  and  $\sigma_{xy}$  are the local stream-wise standard deviation and the bed form field standard deviation, respectively, for  $i = 1, 2, \dots, m$  and  $j = 1, 2, \dots, n$ . Thus, 3DI ( $T_b$ ) is defined by Eq. (5).

$$T_b = 1 - R^2 \quad (5)$$

Subsequently, the average 3DI of a resolution cell, which is limited by nodes  $\eta(x_i, y_j)$  and  $\eta(x_{i+1}, y_{j+1})$  (Figs. 1-a and 1-b), is obtained by estimating  $T_b$  over a spatial window of arbitrary fixed length  $L_x$  by  $L_y$  being centered in such resolution cell. Finally, contours of  $T_b$  over the whole bed form field are obtained. It is important to note that the aforementioned process excludes the resolution cells of the bed form field periphery; although, the algorithm minimizes the number of such cells.

## 3. Software framework

### 3.1. Software architecture

Bedforms-ATM applications are built to run in successive sequence. This stems from the fact that some of Application 2 input data is Application 1's output data, both Application 3 and Application 4 use Application 1's output, and Application 4 inherits input

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